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DECISION SUPPORT ENVIRONMENT FOR CONCURRENT ENGINEERING REQUIREMENTS

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13. ABSTRACT (Maximum 200 words)

This paper presents the results of internal Air Force Human Resources Laboratory (AFHRL) research investigating the potential applications of Quality Function Deployment (QFD) to Concurrent Engineering (CE). Influences from the Total Quality Management (TQM) initiative, as well as CE, have increased acquisition emphasis on customer satisfaction and proper definition of the "Voice of the Customer." In weapon system acquisition the combat command's requirements are the "voice of the customer" and it is their needs and requirements that must be captured, defined, and satisfied. To help achieve this goal, as well as TQM and CE goals of improved acquisition efficiency and effectiveness, this research investigated the weapon system requirements process. The requirements process was characterized and a set of tools and methods discussed to enhance the process. A decision support environment accommodating the requirements process and incorporating the methods and tools will enhance CE through the earliest parts of design, the definition of the weapon system requirements, and the needs upon which those requirements are based. A finding of the research was that QFD could be used as a paradigm for a Decision Support System (DSS) environment to incorporate the investigated methods, and thereby enhance the requirements definition, analysis, and management aspects of weapon system acquisition.

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SUMMARY

This report documents in-house research performed at the Air Force Human Resources Laboratory (AFHRL) into Decision Support Systems (DSS) applications of Quality Function Deployment (QFD) to improve the weapon systems requirements process. Invoking Total Quality Management (TQM) and Concurrent Engineering (CE) principles, the research identified tools and techniques which if coupled with QFD-like technology, would improve the requirements process.

TQM and CE are traced to the requirements determination process and customer involvement in that process. Since the focus of this research was to enhance the requirements process, a separate section is provided to define and characterize requirements and the requirements process as well as describe, in general terms, the Air Force requirements process. Having thus characterized requirements and the process, the next section of the report presents various tools and techniques, which can enhance the requirements determination, analysis and management functions within weapon systems acquisition. QFD is then described along with a brief history of the technique.

The purpose of the requirements characterization and the discussion of the various tools and techniques is to present a framework within which to define a decision support environment adequate to accommodate and enhance the CE requirements process. Since QFD is seen as a potential solution to the challenge, the QFD section is intended to provide the reader with sufficient background and understanding of the QFD technique to realize the opportunity QFD offers. Coupling aspects of QFD with decision support technology provides an environment that offers a potential solution to problems within the requirements process.

The paper concludes with a summary of the issues raised and findings determined through the investigation of applying QFD to CE via decision support technology for the weapon system requirements process.

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PREFACE

The purpose of this paper is to document the work performed and research findings resulting from an in-house research effort investigating the application of Quality Function Deployment (QFD), and its matrix-based graphical presentation devices, to Concurrent Engineering (CE). This investigation necessarily examined the background of QFD and CE as well as the Total Quality Management (TQM) initiative, the impetus for the CE initiative. The investigations quickly focused in on the requirements process within the weapon systems acquisition process. Both TQM and CE place heavy emphasis on properly defining requirements. Thus, this paper describes TQM and CE from the requirements perspective, characterizes the requirements process, and defines a set of tools and techniques to enhance the process. The paper also describes QFD to present the technique as a potential solution to the requirements process improvement effort called for by TQM and CE. The investigations are built upon previous research accomplished in the Decision Support Systems (DSS) area. The resulting findings and conclusions comprise the conceptual foundations for a research program in DSS to enhance the weapon systems requirements process.

The in-house research was not a sole venture, as the author had considerable help. The ideas, insights, and particularly the graphics were the result of a research team from the Logistics System Branch: Captain Steve McClendon, Mr Brian Smith, and Mr Matt Tracy. Additional assistance came from Dr Michael Wolfe, a Summer Faculty Research member of AFHRL during 1989, and from fellow branch member, Captain Michael Painter.

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FOR
CONCURRENT ENGINEERING[1] REQUIREMENTS

I. INTRODUCTION

The purpose of this report is to describe the background and foundations of a new research effort within the Logistics and Human Factors Division of the Air Force Human Resources Laboratory (AFHRL). The broad purpose of this research is to improve the tools and techniques used within the weapon systems acquisition process. Specifically the objective is to define, develop, and demonstrate computer-based tools and supporting methodologies to enhance definition and design efforts early in the weapon system acquisition process. How early? Effective tools and methods are needed from the time a weapon system need is first conceptualized until that system is decommissioned. Since such turn-key systems are often too large to bring to reality, the research effort discussed herein specifically targets the requirements process (definition and management) within the weapon system acquisition process.

This research has evolved from several related research efforts. Within AFHRL, this research had its beginnings in the Decision Support Systems (DSS), Integrated Design Support (IDS), Unified Life Cycle Engineering (ULCE), Reliability, Availability, and Maintainability in Computer-Aided Design (RAMCAD) and more recently the Concurrent Engineering (CE) program.[2] For the most part, these efforts explored computer-based solutions to different functional aspects of the weapon system design problem. The studies accomplished and technology developed under these efforts targeted the design process within industry to improve the design and development of industry's products in response to government statements of work, and specifications.

Similarly, other DoD initiatives and research have targeted the design, manufacture, and life cycle support of the weapon system. Most notable among these efforts are Computer-Aided Acquisition and Logistics Support (CALS)-related programs and, more recently, the DARPA Initiative in Concurrent Engineering (DICE). Figure 1 provides a brief overview of these research influences.

Recent initiatives in DoD to improve weapon system acquisition, and DoD management in general, have introduced additional perspectives to the design and development process. Most notably, the Total Quality Management (TQM) initiative, followed by the Concurrent Engineering

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[1]Concurrent Engineering is synonymous with other terms such as Concurrent Design, Simultaneous Engineering, and Integrated Product Development (IPD). This report uses just the CE term.

[2]See Appendix A for complete list of publications produced from the AFHRL DSS effort.

initiative, have increasingly emphasized on properly defining "what" a system is to do and "why" it is being built. In other words, what are the requirements for the system? What does the customer want and is he satisfied with the product? Is the system being properly defined up front so it is built right the first time?

| | CALS ⟶ (early) | RAMCAD ⟶ | ULCE ⟶ | Concurrent Engineering | |
				(Narrow View)	(Broad View)
Development Phases	Detailed Design Production & Fielding	Preliminary Detailed Design	Conceptual, Preliminary, & Detailed Design	Preliminary, Detailed Design	Pre-concept through Fielding & Disposal
Downstream "ilities" Considered	Supportability (Technical Data)	Reliability, Availability, Maintainability	Supportability, Producibility	Producibility	All that are appropriate to the problem at hand
Implementation Mechanisms	Computers (CAD/CAE)	Computers (CAD/CAE)	Computers (CAD/CAE)	People (Teams) DFMA Methods	People (Teams) CAD/CAE DFMA Methods Quality Methods (QFD, Taguchi, Deming, etc.)
Proponents	OSD	USAF, ARMY	USAF	SME	OSD/DARPA

Figure 1. Related Research Efforts

Structure of the Paper

Both TQM and CE heavily influenced the current research. While it is not the purpose of this paper to thoroughly address TQM, CE, and their interrelationship, it is important to understand some of this background, particularly with respect to requirements. This background discussion is the subject of Section II.

Sections III and IV present the conceptual basis for this research. While Section III presents information influencing the research, Section IV presents actual findings. Since the effort focuses on requirements, Section III starts with a discussion of requirements characterizing the activities and perspectives embedded within the requirements process. From this, the discussion proceeds into a series of tools and methods, which if embedded within a DSS, enhance the activities within the requirements process.

One key theme of the TQM and CE initiatives is increased emphasis on methodologies to improve product and process quality. Some examples are process improvement teams, Taguchi experiments, design of experiments, Statistical Process Control, and Quality Function Deployment

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(QFD). The examinations of QFD as a technique to improve design within a CE environment underscore the research results presented. Section V provides a brief overview of QFD. The benefits of QFD, as described in Section V, include many of the same benefits as CE. Coupling QFD-based decision support tools into a CE environment brings further benefits to CE. The purpose of Section V is therefore to familiarize the reader with QFD and some of the inherent benefits of the methodology, particularly as these benefits present a solution to the requirements process problem addressed in Sections III and IV.

Finally, Section VI presents early conclusions derived from the research along with various issues and observations raised during the research.

II. BACKGROUND[3]

Total Quality Management

The DoD adoption of TQM coincides with a reawakening of quality throughout American industry.

> Reawakening of American interest in quality control can be dated
> from about 1980 when it had become apparent that Japanese
> companies were posing a serious competitive challenge to American
> companies in one industry after another [Roberts, undated].

Ironically, American industry is rediscovering quality philosophies and quality techniques from foreign countries, most notably Japan, based on American philosophies and techniques The most notable proponent, and an originator of the philosophies underlying the DoD TQM initiative, is Dr. W. Edwards Deming. In 1980 Deming was reintroduced to America in the NBC White Paper, "If Japan Can, Why Can't We?" [Garner and Naughton, 1988].

While Deming and his philosophies are regaining fame and acceptance in America, his reputation in Japan is legendary. Brought to Japan after WWII (as were others including J. Juran) to assist in Japan's reconstruction efforts, Deming preached the essential role of management and statistics in producing an organizational culture focused on quality [Deming, 1986]. Deming told Japanese top management this focus on quality was essential to their industrial survival and this focus would bring industrial competitiveness along with increased industrial market share. Deming claimed Japan would become an industrial world leader if his philosophies were adopted. The Japanese listened and now, ironically, it is American companies that travel to Japan to learn the

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[3]Some of this section appeared in precursor work, Hill 1990a and featured in Hill 1990b. A recent, more detailed examination of the history of TQM is in McGovern 1990.

secret of the Japanese industrial success, such as in the DoD-sponsored Technology Assessment Team on Japanese Manufacturing Technology [TAT, 1989]. Deming's role is signified in Japan's much coveted Deming Prize, Japan's highest honor for organizational quality.

Why didn't Deming work here in America? The answer is he did. The problem is that after WWII American management just quit listening. The massive war production effort caused tremendous shortages of all goods. The U.S. War Department brought "statistical control" into the war effort to deal with the necessarily large production volume required to feed the Allied war-machine. These statistical techniques, classified during the war effort, were developed by Walter A. Shewhart at Bell Telephone Laboratories during the 1920s, and Shewhart's concepts of "acceptable quality level" and "controlled processes" had tremendous appeal to military production personnel. Deming was a Shewhart disciple and active during the war training producers in these quality techniques.

When the war ended, industry had an eager market, full of purchasing power, ready to devour all the products industry could provide. America had developed a sort of "purchasing potential" just waiting for a release. Couple this market with an intact industrial base (something America had while most of the rest of the world had to rebuild), and the result is an environment focused on meeting schedules and market demands. As J. Juran notes, "What emerged was a concept in which upper management became detached from the process of managing for quality" [Juran, 1989]. American management simply lost interest in a quality emphasis. Deming took note of this trend, and when sent to Japan, sought to avoid the American situation by first developing "management commitment" to quality. This key role of management in the quality improvement effort is now fundamental to all of Deming's teachings.

A somewhat similar occurrence took place in the DoD sector. As noted by E. N. Luttwak, America won WWII by a strategy of "reorganize and out-produce." The Allied effort won out over the Axis powers due to their (American) ability to out-produce and then numerically overwhelm the enemy [Luttwak, 1984]. The DoD retained a production emphasis until the mid-1960s. During the 1960s, US strategy moved away from numerical superiority to a strategy of "qualitative superiority" [TAT, 1989]. Under this strategy, military weapons, though fewer in number, are technologically superior, thereby offsetting the numerical imbalance. This means that fewer weapons are produced. This has caused a deemphasis in manufacturing as the means of production [TAT, 1989]. The lucrative position enjoyed by American industry as a whole after WWII lulled industry into a false sense of security about the quality and competitiveness of its products.

Another factor to consider is American research and development (R&D) emphasis on basic research. American R&D, through government and commercial laboratories, typically promote product innovation versus improvement of the production processes. The American strategy is to

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demonstrate the technology and then let manufacturing worry about producing the product. This approach pervades American culture. US companies spend about two thirds of their R&D money on new product development while Japanese companies spend this same percentage on manufacturing process improvement [Berger, 1989]. US policy for science and technology has basically ignored manufacturing research focusing instead on basic research [Berger, 1989]. So while America remains the world leader in basic research, it has trouble "bringing the products to market" and then remaining in the market for the long run [Dertouzos, et al., 1989].

The DoD acquisition process possesses a similar lack of emphasis on manufacturing (production) research and issues. Thus, all too often weapon systems falter in the transition from development into efficient mass production. Furthermore, the defense manufacturing base is not flexible enough to efficiently handle the short production runs characteristic of defense production caused by our qualitative superiority strategy. This manufacturing situation is a very real concern in the DoD where high production rates are often not possible, yet there is still the need to reduce production to manufacturing transition time. One DoD publication dealing with this issue is the transition templates, DoD 4245.7-M, "Transition From Development to Production."

Since WWII, foreign countries, most notably Japan, have quietly pursued manufacturing excellence predicated on commitment to quality in their products and their processes. The end result is a "crisis" in American productivity and international competitiveness [Dertouzos, et al., 1989]. Whether the perceived crisis is real is the subject of much debate [Berger, et al., 1989; Dertouzos, et al., 1989; Reich, 1989]. The crisis concerns the military because the military is one of American industry's more valuable customers.

> Government is at once the biggest customer and the biggest supplier
> in America [Perry, 1986].
>
> Today, the US Department of Defense is a major customer of more
> than 215 industries, purchasing products that range from office
> supplies and clothing to high-performance aircraft. It is often
> difficult to draw a clear-cut distinction between the US defense
> industrial base and the US commercial manufacturing economy
> across this spectrum. For this reason, the department has a major
> stake in the state of the nation's competitive posture [McCormack,
> 1989].

Industrial competitiveness affects the American industrial base and the ability of this industrial base to meet weapon system development and production demands, particularly in wartime. An inadequate industrial base can lead to military disaster when industry fails to respond to wartime mobilization needs [Berry, 1988]. In addition, the DoD faces contracting with foreign-owned companies. An article by Lawrence C. Grossman [1989] addresses this specific issue:

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> Foreign takeovers present a real concern to DoD. That is foreign owned companies involved in sensitive contracts.

> Many defense analysts argue that foreign takeovers are accelerating the erosion of the U.S. defense industrial base, placing national security in jeopardy.

The DoD's response to the decline of American quality, the lack of emphasis c manufacturing, and the erosion of industrial competitiveness, is TQM.

> The need for a TQM strategy in DoD stems from economic events at the national level. First, the US is being faced with an accelerating balance of trade deficit that affects most major industries. Second, US industry and the economy as a whole have suffered from lagging productivity improvement. Finally, the performance and reputation of US goods and services has decreased simultaneously [Motley, 1989].

Naturally, the DoD acquisition community is the focus of TQM activity. The acquisition community is the DoD interface to the industrial base. In fact, Robert B. Costello said, "TQM is our way-of-life approach to conducting the defense acquisition process" [Costello, 1989]. But not only is the acquisition community the industrial base interface, the acquisition community has long been the target of scrutiny, and some rather scathing texts have been written on the subject such as Luttwak's [1984]. In particular, the need is for the acquisition community to streamline operations, reduce bureaucratic overhead, and better produce weapon systems for the DoD versus the individual Service preference.

Concurrent Engineering

Under the TQM umbrella, DoD tasked The Institute for Defense Analyses (IDA) to examine claims that CE was a key technique to improve product quality while lowering product development time [Costello, 1989]. The IDA study strongly supported the claim and recommended DoD adoption of CE as a critical technology for meeting TQM goals and objectives. On Mar 9, 1989, Under Secretary of Defense for Acquisition, Robert B. Costello issued a memorandum "Concurrent Engineering - A Total Quality Management Process." With the issuance of this memorandum, CE became a critical technology of the DoD TQM initiative [Costello, 1989]. The IDA Report, "The Role of Concurrent Engineering in Weapon Systems Acquisition" stated CE could "contribute to our Total Quality Management (TQM) objectives of reduced cost, reduced time, and improved quality" [Winner, et al., 1988].

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The DoD adopted CE and the now accepted definition of CE put forth by IDA is:

> Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements [Winner, et al., 1988].

But some might claim, and have a good argument, that CE is merely systems engineering (SE) by a different name. The Defense Systems Management College definition for systems engineering is:

> Systems Engineering is the application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional and program interfaces in a manner that optimizes the total system definition and design; (c) integrate reliability, maintainability, safety, survivability, human, and other such factors into the total engineering effort to meet cost, schedule, and technical performance objectives.

As discussed in Wiskerchen and Pittman [1989], systems engineering has been a very successful technique in past DoD development efforts dealing with large, complex systems. Successes noted include the Explorer I satellite launch and the landing of a man on the moon. There have, however, been notable failures as well, such as the Sergeant York air defense gun and the space shuttle [Wiskerchen and Pittman, 1989].

The classic systems engineering model as depicted in Figure 2 doesn't appear robust enough to handle the design, development, and acquisition of modern weapon systems. The model is simply too restrictive. Modern weapon systems are too complex, satisfy too many functional requirements, and take too long to design, acquire, and field to follow what is perceived as a sequential, management-review oriented approach to weapon system design. A more robust design methodology is required, one dynamic enough to handle modern weapon systems design and development [Wiskerchen and Pittman, 1989]. Naturally this view of the SE model might cause discussion. After all the model is really just a framework adapted to the particular implementation, and there is no reason why iteration can not be accommodated. The point being made here is that the SE model might promote implementations not robust enough for modern design and development efforts.

The CE model (Figure 3) represents a subtle change to systems engineering. Rather than the sequential, management-review oriented perspective of the previous model, CE provides

concurrent product and process development, complete with the iterations inherently present in more complex design situations.

> CE is basically systems engineering except systems engineering focused on the product, not the process. Good companies have been bringing people together to solve problems for years. CE is just the application of systems engineering principles and of management approaches.
> .
> .
> Integrated engineering of products and their associated production and logistics processes with the objective of providing a product and production process that is robust during manufacturing and customer use. The engineering process integration begins at requirements definition and continues through production operations and the products life cycle [Diaz, 1990].

Thus, as pointed out by Hutchison and Hoffman [1990], the goal of CE is "to achieve mutual optimization of a product's critical characteristics and its related processes." Computer tool vendors have made great strides towards optimization of a product's critical characteristics. There are multitudes of computer-based tools to help effectively and efficiently design a product and the manufacturing processes to build in the product's characteristics. For example, Computer-Aided Design (CAD) tools now provide for on-line reliability and testability analyses while the design is still in the drawing stage. Other tools provide capabilities such as assessments of the producibility of mechanical parts prior to generation of the numerical code controlling the machining process [Mayer, et al., 1990]. In fact, it has been pointed out that CE is nothing more than the original SE process; it is just that computer technology has enabled designers to handle the complexity and data requirements associated with the weapon system design process [Tetmeyer, 1990]. But the coming of age of computer tools is just one aspect of CE differing from SE.

Sequential Engineering

Requirement ----→| Product Development ----→| Product Prototype ----→| Process Development ----→
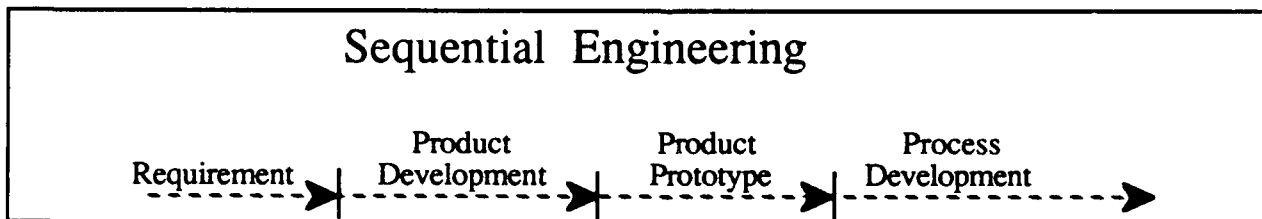
Figure 2: Systems Engineering Model
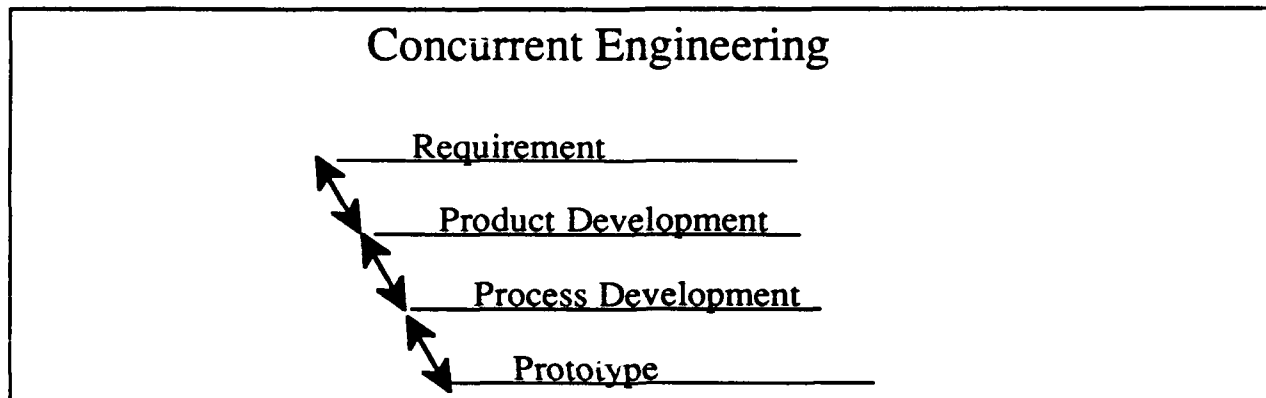
Figure 3: Concurrent Engineering Model

So while CE tool development, such as the above examples, has garnered the largest amount of support to date, there are actually at least eight dimensions to CE.[4] These are:

- top-down systems engineering approach,
- cross-functional development teams,
- interdisciplinary work groups,
- quality engineering methods,
- integrated computer-aided engineering environments,
- focus on the customer and customer requirements,
- improved design processes,
- improved management of the design process.

Where CE really departs from systems engineering is that CE recognizes the important role of the designer, the design team, as well as the computer tools necessary to realize the system design.

> As practiced in Japan, it (concurrent design or concurrent engineering) is a group process where members of the group represent interests spanning the life cycle of the product [TAT, 1989].

Applying CE concepts and philosophies to the government side of the weapon system acquisition equation is just as critical as DoD promoting adoption of CE by defense contractors. In one sense, the DoD acquisition community's customer is industry. The DoD products are the statements of need, statements of work, requests for proposal, etc. that form the basis for the development effort. The better we in the DoD produce our products, the more we satisfy our customer, industry. In turn, the DoD is industry's customer. Industry returns to DoD the systems

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[4]These dimensions are drawn in part from the work of Mayer, et al., 1990.

developed as part of the contracted efforts. It is a chain of interdependencies only as strong as the weakest link in the chain.

The CE effort, as well as the TQM effort, within the government is large and has to be worked by many people at different levels of responsibility to make the effort work. For instance, consider the following comment by Secretary of Defense Cheney in Kitfield [1989]:

> At the heart of our (DoD) effort to reform the management of the Pentagon lies the challenge of persuading members of Congress that they have imposed an awful lot of limitations and restrictions on the department that make it very difficult to us to do our business.

The limitations and restrictions within the acquisition process can only be changed at the highest levels of DoD acquisition management. Even changes in the requirements process have aspects properly considered at the highest level. As indicated in the Packard Commission Report, A Formula for Action, blending requirements from user and technical aspects is a very difficult process requiring "a blend of diverse backgrounds and perspectives that, because the pressures for goldplating can be so great, must be achieved at a very high level in DoD" [Perry, 1986].

The necessary changes at the high levels of DoD management are a common subject in DoD acquisition literature. The DSMC publication, Program Manager, contains a column whose subject is the current status of acquisition improvement. Reports, articles, even books, such as those by Kent [1989], Ferguson [1990], and Record [1988] examine possible solutions to these DoD-level issues. Regardless of the macro-level structure changes, there will always remain the worker-level requirement to function within that structure to define, develop, and deliver weapon systems into the DoD inventory. Thus, while TQM and CE have objectives at the macro-level structure of weapon systems acquisition, both initiatives bring influence into the worker-level, the micro-level, aspect of weapon systems acquisition.

From an acquisition standpoint (and manufacturing in general), TQM "starts with the correct definition of user requirements" [Strickland, 1989]. While aspects of the weapon systems requirements process are changed at high levels, the fundamental need for a new system and the requirements that characterize that system are in fact handled at a much lower level in the DoD management bureaucracy. CE is "characterized by a focus on customer requirements" [Winner, et al., 1988]. This is one of the strongest links between TQM and CE. The requirements process is so important to concurrent engineering and system acquisition in general, that the focus of this particular research effort is on improving that process.

In DoD acquisition, the ultimate customer is the system user, the soldier in the field. If a system is designed and produced to meet every specification perfectly, it is still not a "quality" system unless the system is usable by the soldier in the field. Thus, the acquisition community

marches to a dual concept of quality. Quality in Fact examines whether the system is built correctly. Quality in Perception examines whether the user likes the system and whether it meets his needs.[5]

> The combat command's requirements are the 'voice of the customer'
> to which all development and supporting agencies must respond.
> The USAF customer has spoken and the words are Combat
> Capability [Goodell, 1988].

While referring to the USAF R&M 2000 process, Brigadier General F. Goodell, USAF/LE-RD,[6] captured the essence of TQM and CE; requirements feed the entire acquisition process.

How can the process be improved? Improved communication with the user is one way. Improved communication among the design team members is another. This requires bringing together as a team, personnel from the various functional areas to address critical life cycle issues early in the design process, while at the same time facilitating communication among the team members. The SE process must also be improved by CE concepts to increase discipline in the requirements definition process and focus design efforts on satisfying the customer requirements. The tools and techniques to define, analyze, and manage requirements for a weapon system must be adequate and integrated to promote efficiency within the requirements process. Adequate tools must fit into and enhance the requirements process. The next sections describe the requirements process from a somewhat abstract point of view and then describe a set of tools and techniques that enhance the process. The purpose is two-fold. First, an adequate decision support environment must fit the described environment, and second, the components of that support environment must enhance the environment.

III. REQUIREMENTS PROCESS

All systems are designed and built to satisfy a set of requirements. These requirements arise with the identification of a weapon system need to meet an operational threat scenario. The process by which these needs are determined and defined is the critical first step in the acquisition process. Since requirements are the foundation for effective systems development, a goal of CE is to improve the requirements trade-off process while moving the process into the earliest stages of the acquisition. Thus, better methodologies and supporting computer tools are necessary to

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[5]These concepts of Quality in Fact and Quality in Perception come from Townsend and Townsend's 1986 book, Commit to Quality.
[6]USAF/LE-RD is now designated SAF/AQXE.

enhance the requirements environment. Any attempt to build tools and methodologies must be preceded by developing an understanding of the current environment.

What exactly is a weapon system requirement? From the Air Force Institute of Technology (AFIT) [AFIT, 1990], a requirement is "the need or demand for personnel, equipment, facilities, other resources, or services, by specific quantities for specific periods of time or at a specified time." Two related, more specific definitions also come from AFIT. First, a required operational characteristic is "a system parameter (or set of) that are primary indicators of the system's capability to be employed to perform the required mission functions, and to be supported." A required technical characteristic is "a system parameter (or set of) selected as primary indicators for achievement of engineering goals. These may not be direct measures of, but should always relate to the system's capability to perform the required mission functions, and to be supported." [AFIT, 1990].

The AFIT set of definitions imply a specified system, parameterized and quantified. Further, this set implies a somewhat static environment in which the requirements are set and remain relatively stable from then on. Not until full-scale development will such a set of requirements become available [Ferguson and Hertz, 1990]. The Pymatuning study on CE labeled this characteristic of requirements as a "lack of clarity in the definition of the requirements" citing the characteristic as one of two inhibitors within the requirements specification process.[7] This inhibitor "results in an inability to define real requirements in the early concept and design definition phases of a program." Part of this inability stems from the inability to adequately perform trade-off studies among competing requirements [Pymatuning, 1988].

While the AFIT definitions provide a necessarily general definition followed by two more specific, supporting definitions, a definition by itself fails to explain the more abstract elements of the requirements process and environment. The following discussion seeks to better characterize requirements.

The terms requirements and need seem synonymous. In fact, the dictionary supports this. A need is "something useful, required" while a requirement is "something needed; a necessity." Must there be a distinction? Our research indicates there must be a difference, albeit a subtle difference. Weapon systems are developed to meet operational threats. As stated in Section II, the TQM and CE initiatives must be addressed at various levels in DoD. Operational threats are derived from the National Security Strategy of the United States. One can not get much higher in the DoD. As this strategy permeates through the DoD, operational planners eventually uncover a weapon system "need" to counter an operational scenario. This need is met by existing

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[7]The second inhibitor listed in the Pymatuning report was a lack of a realistic process for generating requirements, a topic addressed by Ferguson and Hertz, 1990.

capabilities, tactic changes employing existing capabilities, or the development and acquisition of new systems (modified or newly developed).

For acquisition efforts, the need undergoes a sequence of redefinitions and transformations referred to as product design and development. This sequence produces an increasingly exact set of limiting conditions (requirements) on the needs that must be met. The end use system should satisfy the final set of requirements defined to meet the previously defined operational need.

The above definitions of need and requirement establish a clearer delineation between a need and the requirements generated to satisfy that need. Having delineated the two terms, we can characterize the overall requirements process as having three perspectives:

- functional perspective,
- hierarchical perspective, and
- bureaucratic perspective.

Within the above perspectives are three aspects (or phases) of requirements. These are:

- definition of requirements,
- analysis of requirements, and
- management of requirements.

At any point in time, personnel involved in the requirements process operate in a single dimension of the process, We define dimension to mean operating in a particular perspective while working on a particular aspect of the requirements. While that person will not make a conscious decision to work that particular dimension (perspective + aspect) of the requirements, understanding this dynamic interaction among perspectives and aspects is quite useful, not just an academic exercise. One immediate use is to develop DSS technology. To build a DSS that effectively enhances the overall requirements process and environment requires that the DSS accommodate this dynamic interaction. Thus if we can build DSS technology to accommodate any of the possible dimensions of the requirements process, that DSS can enhance all phases of that requirements process.

Perspectives of Requirements

A requirement perspective addresses how to view the set of requirements. One might say a design is just a design and a "perspective" is just a useless abstract concept. However, how one examines that design truly is dependent upon the job at hand (the person's position plus current task). This is their perspective. The ability to examine design data (manually or computer-assisted) in a manner conducive to successfully completing the job is essential.

Bureaucratic Perspective

The nature of requirements necessarily changes based upon the level of management review. For instance, during full-scale development, a program manager is concerned with functional requirements for the system. At the same time, however, Program Element Monitors (PEMs) at the Headquarters level are less technically inclined. Thus, requirements tend to aggregate and become more general as those requirements are reviewed up the management chain. It is this perspective that causes improvements in the requirements process to require efforts at all levels of the DoD acquisition management chain, since all levels are involved in the requirements process. The bottom line is that the level of detail, or level of aggregation, with which one views a set of requirements depends upon the management level or management role of the individual.

Functional Perspective

Any weapon system is a composite of many items (e.g., engines, airframes, avionics, etc.) and related supporting resources (e.g., training pipeline, logistics support, etc.). Each piece of this complex weapon system has characteristics, which in a sense comprise the full suite of the weapon system requirements. At any instance, this full suite of requirements might be examined by one particular functional specialty. Thus requirements have various functional perspectives embedded within the full suite designed to satisfy this functional perspective need.

For example, the classic pre-CE analogy of design was an environment of "over-the-wall" design handoffs. Here, design engineers did their job relatively isolated from considering other functional areas. The designers created the design and handed the design to manufacturing personnel, for example. Lack of communication was "the wall" over which the designs flowed. In a CE environment, with its multifunctional teams, designs are examined by all team members concurrently. Thus, a design engineer, maintainability engineer, and logistics support analyst may view a design with each trying to improve the design from their functional concern but cognizant of the other person's concerns. Each takes a different "perspective" of the same design. The aggregation of each perspective's input comprises the full design.

Hierarchical Perspective

The hierarchical perspective addresses the evolving nature of requirements in terms of level of design detail. Initially, system requirements are very broad system-level requirements emanating from operational needs (e.g., Statement of Operational Need (SON), and Statement of Operational Requirements Document (SORD), etc.), system level specifications (e.g., system specification, Type A), through detailed design specifications (e.g., Type C).

In a very real sense, these levels of design detail represent an evolution of the requirements (via a hierarchical decomposition process such as implied by the systems engineering approach)

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incorporating increasingly restrictive technical characteristics.[8] Therefore, at any point during the design process one may wish to view requirements at a particular level of design. Breaking requirements into lower levels of detail facilitates the engineering task.

For example, reliability engineers may examine a system design at a functional block level, followed by subsystem high-level design, or at the board or component level. Exactly how the design is viewed depends upon the level of design detail achieved; it depends upon how far the design decomposition has progressed. Furthermore, a decision at one particular level of design may affect decisions made at other levels of design. The engineer needs the capability to move between design levels.

Aspects of Requirements

A requirement is defined, it is analyzed/modified, and it is managed. We define these as the three aspects of requirements. Techniques (manual or computer-assisted) that aid in accomplishing tasks in these aspects save time, provide more complete and thorough processing, and ensure consistency among the requirements. The three aspects defined are similar to those posed by Ferguson and Hertz [1990] in relationship to defining the term requirement:

> The definition of requirement depends on where one is in the requirements planning process. Requirements planning begins with an examination of the operational need. It continues as weapon system alternatives are evaluated according to how well they allow us to fulfill operational requirements. Finally, requirements planning makes trades in performance, cost, and schedule to determine the optimum system performance.

Requirements Definition

Requirements are defined as those efforts focused on determining operational behaviors of the final, fielded system. The personnel initially involved in such efforts are concerned with system capabilities to meet operational threats and mission needs. The analyst/planner defines operational concepts to meet operational needs. Using knowledge of current system capabilities the analyst/planner correlates operational needs to existing capabilities. This correlation activity enables the planner/analyst to determine voids in current capabilities thereby defining requirements for new development or current system modification. This need determination is the earliest requirements determination effort.

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[8]Restrictive in the sense that as design detail is added, the set of feasible designs is reduced.

As this need undergoes iterations of redefinition and transformations, the need generates a set (or sequence of sets) of requirements defining the weapon system. During each iteration, input is in the form of needs and previously defined requirements. Personnel involved take this input and determine the requirements for their particular perspective. Thus a supporting discipline, such as manpower, personnel, and training (MPT), might examine current design input and determine a set of corresponding requirements reflecting MPT concerns appropriate for the current level of design detail.

Requirements Analysis

While the definitional aspect requires the listing of requirements, the analytical aspect provides the "reality check." A weapon system design is actually a sub-optimized set of requirements from all affected functional disciplines. They are sub-optimized in the sense that each functional requirement might be less than optimum due to its effect on the remainder of the system; it is weakened for the strength of the overall system. It is this analysis, or tradeoff process that is essential to successful development, and the acquisition of weapon systems within cost, schedule, and performance constraints.

Requirements analysis, in this context, is defined as the set of activities involving cost, schedule, and performance trade-offs that attempt to meet the operational needs of the new system. Real-world resource constraints prevent 100% satisfaction of all system needs or requirements. This necessitates rational tradeoffs to support the most critical characteristics of the system. Additionally, requirements from supporting functional disciplines are incorporated into the effort. Such supporting disciplines include reliability, maintainability, logistics support, manpower, personnel, and training, to name a few.

Requirements Management

The last aspect supported is requirements management, which means the e activities associated with maintaining the integrity of the system requirements as the requirements evolve over time. Requirements management deals with those actions necessary to ensure management oversight is properly applied to the program to best correspond to the relative priority and risk associated with each system requirement. Among the issues affecting requirements management are:

- audit trail of requirement changes,
- rationale for determining/modifying requirements,
- impacts on and interrelationships between requirements,
- impacts to cost and schedule due to status of requirements satisfaction,
- consistency of requirements throughout the acquisition effort, and
- systems requirements impact on the other potential/fielded systems.

Air Force Requirements Process[9]

In DoD, the combat command's needs for a system ultimately determine their level of satisfaction with the fielded system. These are the customer requirements for the weapon system. However, systems are built to system design requirements derived from the customer requirements (the combat command's needs). How well a system satisfies the system requirements is indicative of combat command satisfaction with the system only to the extent the original needs were accurately translated into appropriate system requirements.

The vehicle for defining a need and the associated operational requirements to meet that need, are the Statement of Operational Need, the SON. For Joint Service efforts the Joint Service Operational Requirements (JSOR) is the requirements document. The process in place for these documents is found in Air Force Regulation 57-1. The SON establishes the foundation for the acquisition effort. The primary purpose of the SON is to describe the need in operational terms, relating the need to planned operations and support concepts. Its principal uses are to:

(1)   define an operational need,
(2)   obtain official validation, and
(3)   furnish preliminary program guidance.

There are also supporting documents required within the defined process. The System Operational Requirements Document (SORD) refines the elements of the SON explaining how to operate, employ, deploy, and support the proposed system. It details the operational requirements of the system supported by Program Objective Memorandum (POM) funding. Together with the SON, the SORD provides initial program guidance in preparing Requests for Proposals (RFPs), requirements for testing, warranties, program management, and program planning. Additionally, AFR 57-1 requires SORD updates prior to each major program milestone, with changes tracked in the Requirements Correlation Matrix (RCM). These updates provide additional quantitative and qualitative factors on the performance and support characteristics for the system.

As implied above, the RCM is used to track changes to the user requirements (as contained in the SON and SORD) as those requirements evolve over the life of the program. An additional purpose is to provide a means to easily compare how well requirements correlate to specifications and test criteria. The RCM is discussed again in Section V as a tool/technique to enhance the requirements process.

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[9]The details on the SON, SORD, DSRD, and the involved commands, are paraphrased from AFR 57-1, 7 October 1988.

The final document discussed in AFR 57-1 is the Depot Support Requirements Document, or DSRD, which is complementary to the SORD. It describes the plans and requirements for providing depot maintenance and material support to the system described in the SORD.

Four groups are involved in the defined requirements process: the Operating, Implementing, Supporting, and Participating Commands.

- The Operating Command is, as the name implies, the command responsible for operating a system, subsystem or item of equipment.
- The Implementing Command is the command designated by the Air Force Acquisition Executive to manage the acquisition program.
- The Supporting Command is the command providing the logistics support and managing the program after transfer from the Implementing Command.
- The Participating Command is a command, or agency, advisory to the program manager and active in the development of the weapon system. The Supporting Command is in fact also a Participating Command.

With the groups and the documentation defined, AFR 57-1 describes, in a high-level manner, the process by which operational requirements are determined and defined.

This defined requirements process is not, however, as efficient as possible, particularly with respect to the overall life cycle acquisition of the weapon system. The myriad of documents produced by the process (Figure 4, [Stanley and Birkler, 1986]) contain inadequate and often conflicting requirements.[10] Balancing the requirements in these documents is not easy. No single Air Force organization can balance:

(1) technical factors regarding the system,
(2) operational factors regarding the system intended use, and
(3) institutional factors regarding policies and procedures.

> Documentation is currently fragmented across many sources; requirements are inconsistent from one document to another; and it is extremely difficult to correlate key operational, contractual, and test requirements [Stanley and Birkler, 1986].

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[10]See Appendix B for definition of each document name contained in Figure 4 and later in Figure 6.
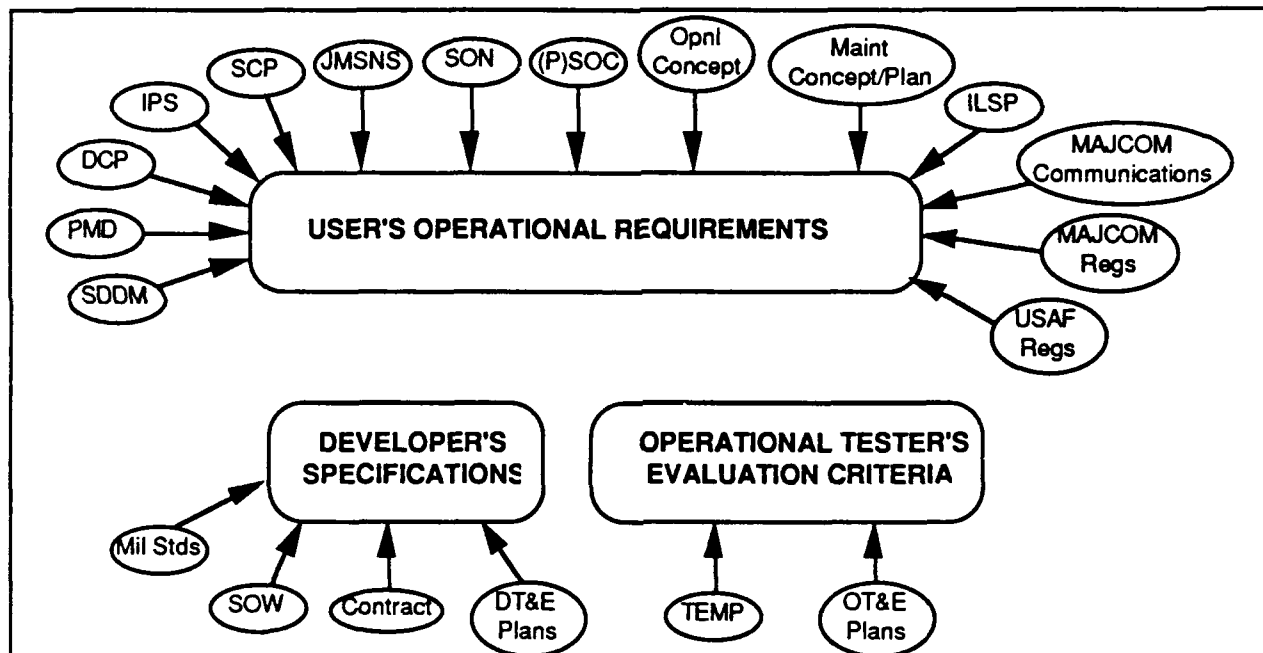
Figure 4. Documents Produced by Acquisition Process

The regulation also defines what the operating, implementing, supporting, and participating commands are relative to the weapon system acquisition life cycle. The combined efforts of these involved commands determine the operational requirements for modified or new weapon systems necessary to meet evolving mission needs. As these operational requirements are defined and evolve over time the SON, SORD, and DSRD documents that propose the requirements and potential solutions are created and, more importantly, evolve.

Detailed in these three documents are not only the mission requirements but also such support functional areas as:

- Availability,
- Maintainability,
- Reliability,
- Logistics Supportability,
- Basing Infrastructure,
- Manpower, Personnel, and Training (MPT),
- Human Factors/Engineering.

The involved commands must consider potential system solutions to meet and sustain the operational objectives. An essential element of their efforts is consideration of the various support functional options in terms of operational criteria, trade-offs within the functional area, and trade-offs between the functional areas and the mission requirements.

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The knowledge required for these considerations is based on experience with current operational systems. Thus, the involved commands rely on experts involved in similar system development, or they rely on the adequacy of their historical databases and subsequent analyses to produce the necessary criteria (e.g., figures of merit, measures of merit, quantitative operational criteria). Additional knowledge comes from various standards, guidelines, and lessons learned. The key point is that a wide range of data is available, and should be made available to the personnel involved in the requirements process.

Just as important as accessing the data to develop the necessary criteria is using the data effectively to define the operational requirements. Understanding the overall requirements process, from need identification to the ultimate fielding of a system, is a prerequisite for anyone involved in the acquisition process. However, such an understanding doesn't prepare an acquisition professional for the task of determining, for instance, the supportability criteria necessary to ensure the final operational suitability of a new weapon system platform. But the effective determination of these supportability criteria is crucial to the ultimate success of the system acquisition effort.

Anyone looking back at the late 1980s, early 1990s (and beyond, we hope) will surely characterize the period as one of change. Acquisition streamlining and acquisition reform, a long-standing topic, are currently very important efforts producing many changes.[11] These recent changes in defense acquisition have resulted in changes to the foundation documents in the acquisition process, among those DoDD 5000.1 and DoD 5000.2-M, "Defense Acquisition Management Documentation and Reports" dated 15 August 1990. As changes to these documents ripple through the regulatory guidance, with the resulting changes in procedures, there will likely be fundamental changes to the specific steps and documents required by the requirements process. For instance, DoD 5000.2-M adds a new baseline, The Concept Baseline, approved at Milestone I and applicable to the Demonstration/Validation phase of the project. Such a baseline places a premium on the quality of the requirements definition and analysis aspects during the concept exploration efforts.

While these changes occur, system acquisition personnel will continue to determine requirements for new or modified systems, conduct tradeoffs among system characteristics, and manage development and acquisition efforts. Tools and techniques will change while the fundamental purpose of the entire process remains essentially the same. The remainder of this section examines current tools and techniques helpful in accomplishing that purpose of successful acquisition efforts. Since the purpose of this entire research effort is to enhance the requirements process, these tools and techniques are mapped (in Figure 5) to the requirements, perspectives, and

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[11] Further details can be found in the Packard Commission report, the Defense Management Review, or in numerous Program Manager articles.

aspects previously defined. While each check or cross mark is not explicitly explained, the indicated correlations help understand the role of the tool or the technique within the requirements process.

IV. APPLICATIONS

Each of the following sections describes a tool or technique applicable to the requirements process. Each is listed on the left side in Figure 5 and its applicability to the perspectives and aspects of the requirements process is indicated by the checks and crosses. A decision support environment that accommodates the perspectives and aspects of the requirements process while including the indicated applications, is a decision support environment adequate for the CE requirements process.

APPLICATIONS	PERSPECTIVES			ASPECTS		
	Functional	Hierarchical	Bureacratic	Definition	Analysis	Management
Need identification	✓		✓	X		X
Template requirements tailoring	✓	✓		X	X	
Analysis of tradeoffs	✓	✓		X	X	X
Rationale capture	✓	✓	✓	X	X	X
RCM	✓		✓			X
BCM		✓	✓	X		X
Baseline control	✓	✓	✓	X	X	X
Requirements traceability	✓	✓			X	X
ECP evaluation tool	✓	✓		X	X	X
Test planning and management	✓	✓		X	X	X
Risk analysis tool	✓	✓			X	X
Audit support tool	✓	✓	✓		X	X

Figure 5. Mapping Applications to Perspectives and Aspects

Need Identification

Need identification refers to those activities involved in examining operational threat scenarios and determining the weapon system behavioral characteristics required to counter the

operational threat scenario. These activities can occur over a relatively long period of time. For instance, concept direction studies lasting 1-2 years fall under this heading. However long it requires, the end result of the need identification activity is a characterization of the operational need (generally system level or operational deployment level) necessary to meet a particular threat scenario, the determination of the extent to which current capabilities (i.e., systems) cover the required characteristics, a general concept of the deployed system, and a general set of cost estimates and programmatic documents necessary to program for the acquisition and development of the system. Dependent upon the concept decided upon, the eventual program may be either new development or modification of an existing weapon system platform.

Currently, this application typically falls under the XR staff function, usually in the acquisition product division, who then work closely with the end user of the system. The products are the concept studies which help produce the SONs, SORDs, and PMDs necessary to commence with the program. From a requirements process standpoint, this application produces the highest level requirements that the final end-use item (system) must satisfy. This is the first stage where the system "customer" must make his requirements known. Once defined, these needs and requirements must be managed for the remainder of the project to track the evolution and incorporation of the requirements into the final system configuration.

The above definition of need identification can expand to accommodate activities throughout the product life cycle. Need identification occurs within each functional discipline as each player on the "design team" defines what is needed to realize the end system. Each player defines his pertinent technical environment, to borrow a concept from the R&M 2000 Process pamphlet. For instance, it is extremely important to address logistics support during the earliest possible stages of the project. As an example, consider two system concepts, one of which functions within the current Air Force basing and support infrastructure, the second requiring modifications to the infrastructure. Such a choice has very different cost and schedule impacts. Failure to consider these issues early might lead to definition of operational requirements to meet a system concept with too large a price tag to be feasible. Such definitional activity continues as the weapon system design is further refined and detailed. At each stage of definition, new requirements are defined based upon previously defined needs and requirements.

Thus, while need identification is typically an initial planning activity, the activities associated with the identification process are found throughout acquisition and development.

Template Requirements Tailoring

From the time an initial need is identified until final design characteristics are defined for component fabrication, the requirements process relies on the past experiences of the personnel

involved in the project. This experience is used to examine the current needs and requirements, and from those, to further derive a set of requirements. In fact AFR 57-1 acknowledges past experience as the primary means of determining SORD and DSRD requirements. This past experience takes many forms, such as personal experience, lessons learned, guidelines, or standards developed to capture individual experts' experience and knowledge. This experience is applied within each functional area and iteratively reapplied as design detail increases through the system design process.

Whatever form this experience comes in, it is a template requiring tailoring to the design task at hand. This template may be the expert's mental image of the system based on the defined requirements. The template may also be lists extracted from the guidelines and standards. Template tailoring is a crucial step in the requirements process, not only to sufficiently define all the pertinent requirements for the system, but also to explicitly examine each requirement against other system requirements. The understanding gained through the analysis of each requirement with respect to other system requirements, and the definition of these interactions serve to delineate a system into the minimal set of requirements necessary to meet a specific need.

Within the acquisition community, tailoring of a standard is already a required process. A standard is a template. Requiring compliance with the entire standard is usually excessive, costly, and inefficient. The DoD recognizes this, and regulations require tailoring. Just as an acquisition officer explicitly considers each requirement of the standard for applicability to the project, so must a functional expert tailor his internal knowledge base and apply that tailored knowledge to the current project.

Analysis of Tradeoffs

Design is inherently a sequence of tradeoffs. Design has also been characterized as merely a decision process [Mistree and Muster, 1990]. From the time various options are examined to counter an operational scenario until a system is fielded, the design and development effort requires tradeoffs among the requirements for the weapon system. The earlier these tradeoffs are accomplished, while maintaining requirement fidelity, the greater the potential for life cycle savings.

CE embraces the multifunctional approach to design. The product and the processes required to produce and support the product are developed in unison. The most successful approach is with multifunctional design teams comprising members from the various functional areas affecting the design. This team approach requires extra effort and extra discipline to reap the rewards of a better design later in the design process.

The team must address requirements from a multidisciplined point of view. Each functional representative defines system requirements necessary to improve the overall design. As these requirements are defined, the interrelationships, or correlations, among other requirements are determined. This determination requires discipline and some extra effort, but must be done to adequately determine the impact a particular requirement has on the overall system. This takes time, not only when each requirement is initially defined, but as each requirement is refined with greater design detail.

This determination effort provides a means for effectively and efficiently conducting tradeoffs among design parameters (i.e., requirements). A proposed parameter change can be analyzed with respect to system performance **and** impacts to other system parameters and support requirements. Conversely, changes to specific system performance characteristics can be analyzed with respect to impacts on defined system-level requirements. The capability produces more complete and thorough analyses of design tradeoffs, particularly as those tradeoffs apply to the tailoring of requirements as discussed in the previous section.

Rationale Capture

Modifications and retrofits to fielded systems are an inevitable part of the weapon system life cycle. The causes of these changes fall into two broad categories: correction of design flaws or oversights, and changes to missions or required capabilities. The CE initiative has a goal to decrease the costs and number of these life cycle support actions. However, this CE goal necessarily applies only to those modifications and retrofits due to design flaws (i.e, poor location for maintenance access, incorrect human factoring, part repositioning for increased reliability). Changes to mission and system end use cause the other set of changes, and since these changes are nearly impossible to predict beforehand, prevent the total elimination of all system changes. We can however ease the modification process by providing the re-designers with the capability to understand the design intent of the original designer involved in the design determination and tradeoff process. This is the concept of rationale capture.

Long after the original design team has moved on, the redesign team needs answers to such questions as:

- Why was a particular operating characteristic required?
- Why was a particular concept selected?
- Why were the particular subsystem location decisions made?
- What were the results of the trade studies performed?

Access to knowledge of previous design decisions allow:

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- Redesign to proceed by reducing the need, or easing the process of, reverse engineering.
- A cost impact assessment applied to the original (and final) design decision.
- A training environment for newly assigned personnel.
- Development of a more effective lessons-learned process.

Rationale capture enhances original requirements processing. Rather than relying on an expert's past experience, personnel involved in the requirements process draw upon past experience captured as design rationale. Designers thus intelligently apply functional characteristics to the evolving design, using the rationale database during the definition and analysis aspects of the requirements process. More importantly, this rationale database provides justification to management for the various design decisions as well as a legacy of sorts on the management of the evolving design.

Requirements Correlation Matrix (RCM)

AFR 57-1 includes the RCM as a required attachment to the SORD. The purpose of the RCM is to provide an audit trail on the evolving nature of the SON and SORD requirements, and a traceability of the requirements in the SORD back to the requirements in the SON.

The RCM is primarily a management tool since the changes tracked are at a high level of design. While the RCM does provide assistance in the functional perspective, such assistance is again at a very general, system level of the design. It is however applicable to correlating user requirements as contained in the SON and SORD to test requirements and specifications.

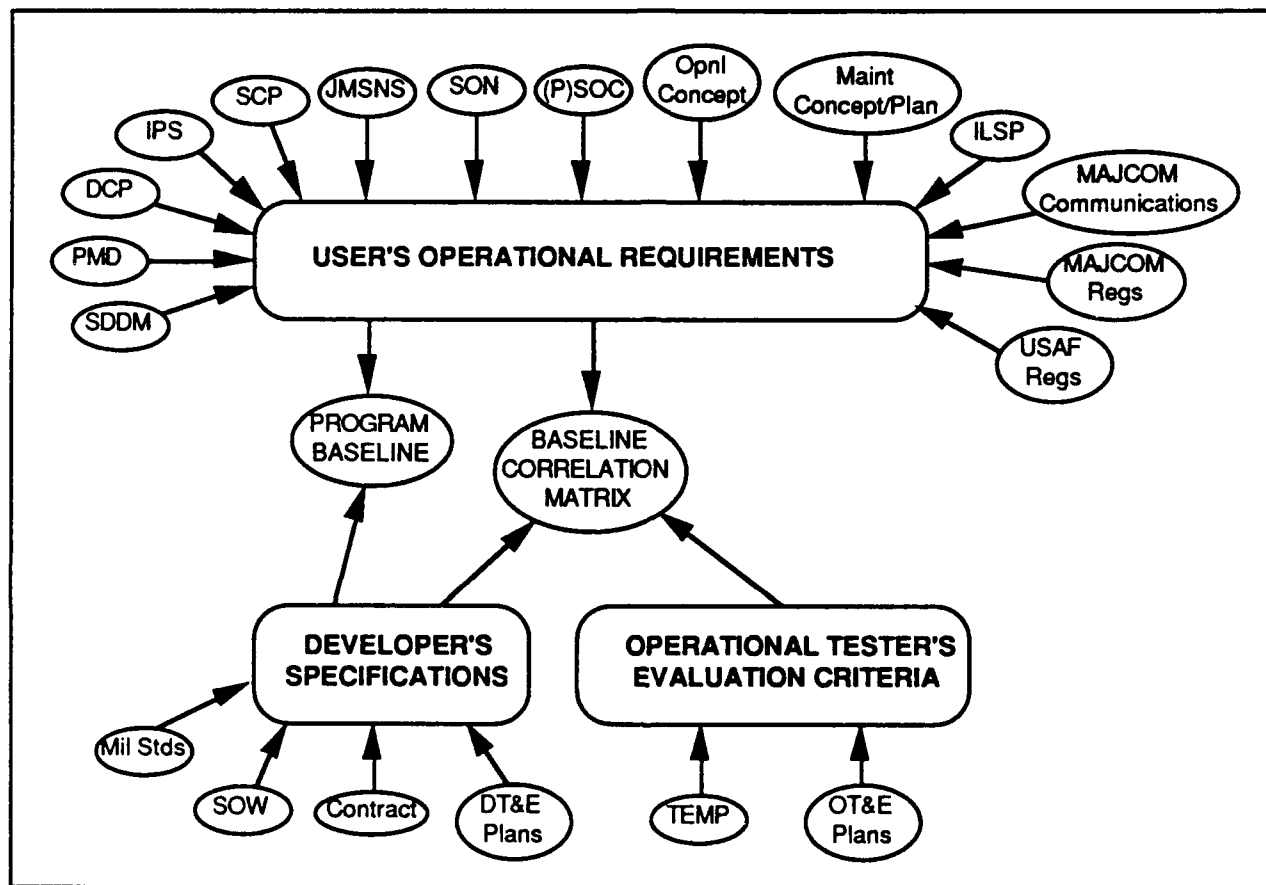## Baseline Correlation Matrix (BCM)

One tool proposed by Stanley and Birkler [1986] is the BCM. Figure 6 depicts its role in the acquisition process with respect to the myriad of documents described in Figure 4.

The role of the BCM is to correlate requirements contained in the program documentation and specifications. Too often requirements provided in one document conflict with those provided in another. The program manager must eventually resolve the conflict; however it is more efficient to avoid the conflict altogether.

Conceptually, a system requirement is contained in the BCM. As that requirement is embedded in program documentation, a relationship is established between the requirement and the documentation entry. This is a one-to-many relationship (one requirement, many documents and entries). Thus, consistency is established among the documents. Furthermore, as these requirements evolve, becoming more definitive over time, the BCM ensures consistency through

the specification levels (hierarchical perspective) and within the functional areas (functional perspective).

The BCM provides the program manager a mechanism to ensure consistency of requirements within the program, program documentation, program baselines, and program test phases, thus avoiding potential conflicts.

Figure 6. Role of Baseline Correlation Matrix (BCM)

Baseline Control

Configuration management (CM) has three main functions, all associated with baselines:

- Configuration identification,
- Configuration control,
- Configuration status accounting.

As a discipline, CM is well defined for hardware and getting better defined for software. As a support function to the program manager, CM is absolutely critical, but unfortunately too often neglected. With pending changes to the acquisition process, CM faces increased challenges as yet another baseline is proposed, the concept baseline.

Baselines are established as development management control points. The baselines serve to document the current, approved configuration of the system and provide a starting point from which to control changes and the change process with respect to that approved configuration. Such documentation and control provide management insight into the acquisition and development process. From a government standpoint, there are essentially four baselines:

- concept,
- functional,
- allocated, and
- production (or developmental).

These can roughly correspond to the accepted SON, Type A specification, Type B specification, and Type C specification, respectively. Although this correspondence is sure to cause immediate controversy, and raise exceptions, the correspondence serves to show that government manages baselines at discrete points within the acquisition and design process. Industry is tasked with building the system to meet the required functional specifications. Industry must deliver the end item and the specifications describing that end item. Thus, industry must manage their baselines in a more dynamic fashion as the design evolves over time, yet incorporate within that dynamic control process, those times associated with government defined review points.

In terms of the requirements process, government needs insight into the specific requirements comprising each baseline, specifically, insight into how the functional requirements are determined and decomposed through the design process and documented in the formal management baselines. This requires management of the requirements, particularly as changes to the various baselines occur. An audit trail of changes to the baseline provides management insight into the design while providing definitional and analytical support to government personnel managing the development and acquisition effort. Baseline control, as a concept, is very closely related to some of the other techniques discussed in this section (e.g., BCM, Requirements Traceability, ECP Evaluation). The point made here is that baseline control is a distinct and important function with respect to program management and the overall requirements process.

Requirements Traceability

Requirements traceability is the explicit establishment of relational links among the requirements of a system. These links establish dependency relationships among requirements across functional disciplines and through the design decomposition process. A waterfall decomposition process as depicted in Figure 13 is very idealistic. Such a pure hierarchical decomposition of independent links is nearly impossible in practice. Real weapon system designs are actually a complex set of interrelationships and decision points. However, Figure 13 can be used to show, generally, how each level of requirements ties back to higher level, and ties forward to lower level requirements. The jump in complexity comes when the linking takes place among functional requirements and through multiple layers of design.

Traceability provides the capability to tie requirements back to the operational threat. The level to which the defined requirements satisfy the defined need gives an indication of anticipated customer satisfaction with the weapon system. Further, changes to design parameters can be analyzed with respect to impacts to the original need. Design parameters that are not directly traced back to an original need might be targets for deletion or require further analysis and definition.

Traceability, in conjunction with the BCM tool, determines how requirements are embedded with system documentation and baselines. For instance, a requirement contained in a SON can be traced through each level of specification through to the test step, or test sequences, that exercise the system to verify satisfaction of the need.

Cost impact relationships for each requirement can be established. Cost estimating during early phases of design is not an exact science, although it is often mistaken to be exact. Various cost models exist for hardware and software systems but typically cost estimates are based on previous experience with similar systems. If actual cost data can be traced back through requirements, and allocated to the high level quantifiable (and non-quantifiable) weapon system characteristics, better cost estimating relationships (CERs) can be established. These CERs are beneficial, not only for new, similar developments, but also for modification efforts on the weapon system.

The desire to establish such a complex network of relational links among requirements is not new. The technological capability to accomplish traceability is now available, and a matrix-based data structure seems the most desirable. The remaining tools and techniques rely quite heavily on traceability as the enabling capability.

ECP Evaluation Tool

The Engineering Change Proposal (ECP) is the program management tool to propose, review, approve, and implement engineering design changes. ECPs are an important part of acquisition management and weapon system development. Traceability capabilities enhance aspects of ECP processing.

As ECPs are proposed, impacts to various requirements are examined. This examination includes impacts to functional requirements, support requirements, and cost and schedule impacts due to the change.

As ECPs are implemented, baselines change. Such changes can get quite complicated. Knowledge of all change impacts and affected requirements ease the change process by ensuring completeness of the change review. This same knowledge, available due to requirements traceability, later enhances baseline control tracking and configuration status accounting.

Finally, ECP cost impacts can be allocated among the requirements affected by the change. Such allocation, again via the traceability tool, enhances cost accounting and later development of more effective CERs.

Test Planning and Management

The basic purpose of testing is to verify the proposed system works as intended and as designed, in both a test and an operational environment. Thus, each portion of a test should correlate to specific requirements for the system. If such a correlation can't be established, the test step is wasted, or unnecessary. Conversely, if a requirement has no corresponding test, the requirement isn't being verified.

If Test and Evaluation Master Plan (TEMP) requirements are linked into the weapon system requirements, via the BCM and traceability tools, TEMP specifics can be correlated back to specific requirements for the system. Again, this correlation ensures proper test coverage.

Once the test is conducted, the test results can be analyzed with respect to the affected design parameters supporting the requirements. One immediate benefit is to develop an impact list to track causes and fixes for failed tests. This capability enhances test management efforts.

Risk Analysis Tool

Program managers place their emphasis on risk areas within the development and acquisition effort. Risk areas can be defined as:

- high cost areas,
- technological uncertainty,

- critical impact areas,
- schedule-critical portions of the program.

Managers need insight into risk areas of the program. They need answers to "what if" questions with respect to cost problems, budgetary fluctuations, technological shortfalls, schedule slippages and so forth. It is therefore desirable to have the ability to generate complete impact assessments based on particular risk areas. Specifying a requirement, or set of requirements, as "risky" provides the ability to assess relative impacts due to the requirement. This then provides enhanced risk management capabilities to the program manager.

Audit Support Tool

As baselines are established and managed, the system becomes a reality. What was once merely a concept in the mind of the user is now a piece of hardware ready for operational use. The end system has one essential purpose: satisfy the end user. All other purposes are secondary. The end user is satisfied (at least in theory) when the system contains all the functionality requested, does so in a manner acceptable to the user, and demonstrates operational capability over time.

Audits provide a confidence check that the system will satisfy the user. The Functional Configuration Audit (FCA) verifies all the functional requirements of the system are in fact designed into the system. The Physical Configuration Audit (PCA) verifies the system specifications accurately and adequately define the as-built configuration of the system.

These audits ensure the conceptual baseline maps to the final production baseline, through the intermediate functional and allocated baselines. If such a mapping cannot be established, the final system has shortfalls. An audit support tool provides a means of explicitly detailing the mapping among and between baseline requirements and can be used as an aid in accomplishing both the FCA and the PCA. This mapping ensures that the functional requirements completely map from the SON through the baselines. Conversely, it identifies requirements that aren't satisfied and the impacts these shortcomings produce. While not intended to eliminate the audits, such an audit tool will enhance efforts during the conduct of the audits.

Decision Support Environment

The purpose of the preceding discussions was to motivate the need for a DSS environment that fits into and enhances the CE requirements process. Some of the tools and techniques discussed are particularly applicable to a decision support environment implementation using matrices. Quality Function Deployment (QFD) is one technique providing the required discipline

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and focus to help improve the requirements process. QFD also employs a matrix presentation scheme. As a paradigm for integration of the tools and techniques into a matrix-based DSS environment, QFD provides a data structuring and presentation scheme for displaying complex relationships. Thus, as both a quality engineering technology for design and as an underlying paradigm for decision support, QFD offers potential solutions to meet the CE challenge of a better requirements process. The next section introduces the QFD structure, technique, and some of the philosophy underlying the technique. The purpose is not to provide a QFD primer, but rather to provide enough background and basic understanding of the technique and its graphical devices that the reader will immediately recognize the QFD opportunity.

V. QUALITY FUNCTION DEPLOYMENT

Organizational Deployment of Quality

The objective of any CE design and development effort is customer satisfaction. As in any quality-based effort, CE requires organizational commitment particularly since many functional areas and management levels are involved in the design and development effort. A popular term is "deployment" of quality through the organization. In CE, as in TQM, there are two organizational dimensions of quality necessary for quality product development. These can be referred to as the vertical and the horizontal dimensions of quality [Sullivan, 1989].

The vertical dimension is intradisciplinary. For instance, within manufacturing, personnel are concerned with conformance to manufacturing specifications. Optimization of the product characteristic is with respect to manufacturing. So in the vertical dimension, design considerations concern just the given functional area.

The horizontal dimension addresses interdiscipline concerns. For instance, how does a design change for reliability affect manufacturing concerns. Design decisions consider impacts across, or independent of, the various functional areas. Sullivan characterizes this horizontal dimension as the "Voice of the Customer" since design considerations are system-wide and typically based on meeting particular requirements for the system.

Figure 7 from Sullivan depicts how such an organization would function and some of the tools enabling the quality deployment effort. Though not addressed in depth in this paper, a large number of organizations, particularly in Japan, are using QFD as a strategic planning tool. The purpose of such efforts is naturally to create an organization focused on quality. By examining the quality efforts across the vertical and horizontal dimensions of the organization, the quality planning effort is more comprehensive.

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This paper focuses instead on the use of QFD as a quality design method. QFD promotes deployment of quality across functional boundaries within the product design effort. It is a method comprising various tools and techniques to translate customer requirements into increasingly detailed design requirements to ultimately embed the customer requirements within product characteristics.
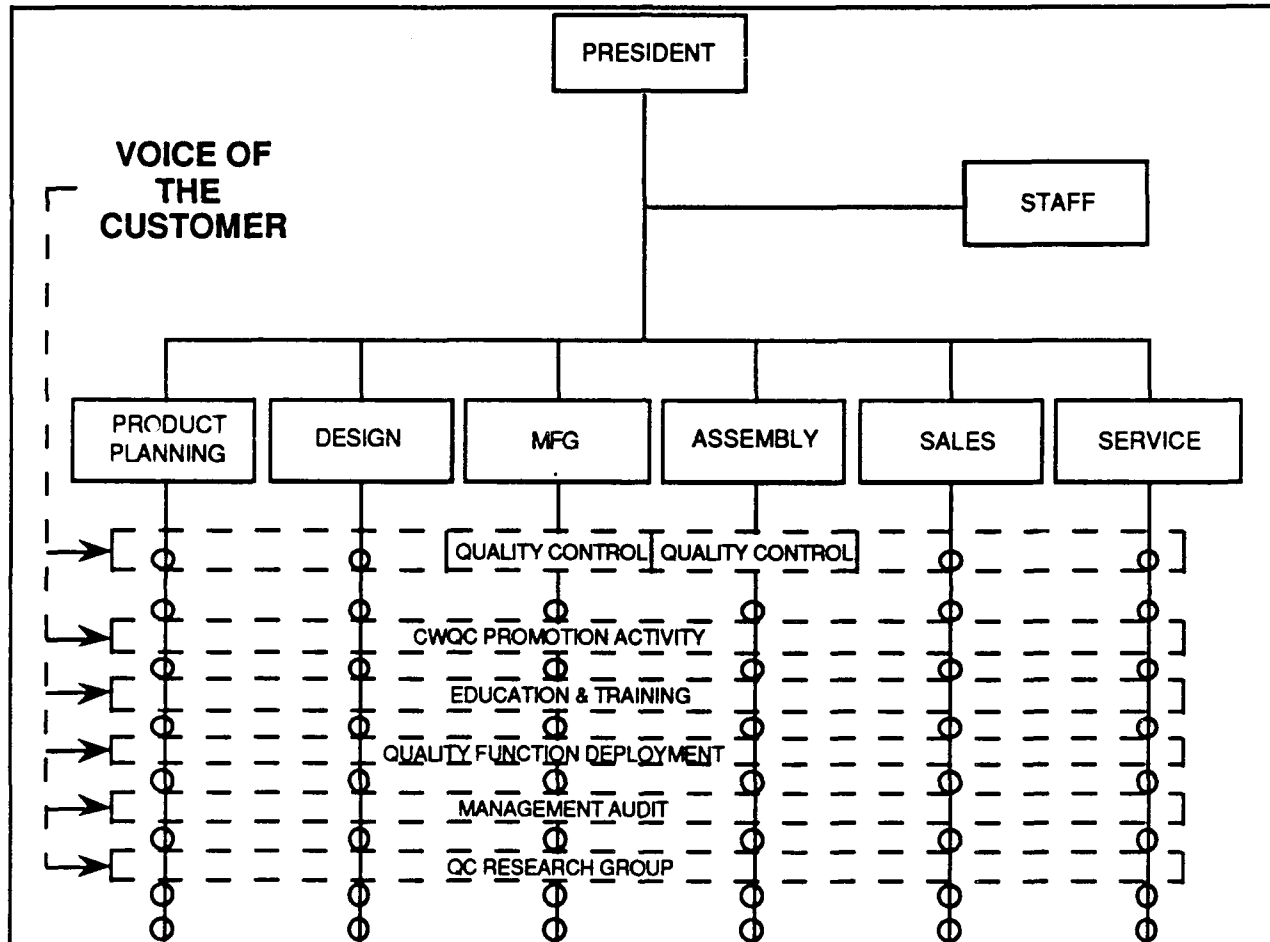
Figure 7: Quality Deployment in Organization

What is QFD?

But what is QFD? There are basically two approaches to QFD. The first approach, the Akao approach as depicted in Bob King's text, Better Designs in Half the Time treats QFD as a methodology employing a matrix of quality charts (a matrix of matrices). These matrix-based charts document the design process. King emphasizes that the real power of the QFD

methodology is not necessarily in completing the matrices, but rather gaining the knowledge and understanding of the system through the **process** of completing the charts [King, 1989].

A second approach to QFD, elaborated in Hauser and Clausing [1988], is called the House of Quality (HoQ).[12] In effect the HoQ approach is a small piece of the methodology described by King. This paper uses the HoQ approach [Hauser and Clausing, 1988; Schubert, 1988 & 1989a & 1989b; Sullivan, 1986 & 1988 & 1989] primarily because the HoQ approach brings more potential benefits to a Decision Support System (DSS) environment for requirements than does the King approach. While King's approach is applicable to DSS implementation, the HoQ approach provides potential capabilities for requirements determination, requirements traceability, and rationale capture; critical elements of the weapon system design and acquisition process discussed in Section IV. The HoQ approach also facilitates the deployment of quality concept thus involving the entire organization. As Hauser and Clausing [1988] point out:

> The foundation of the house of quality is the belief that products
> should be designed to reflect customers' desires and tastes - so
> marketing people, design engineers, and manufacturing staff must
> work closely together from the time a product is first conceived.

Schubert describes the HoQ in his papers, presenting QFD as a framework for accomplishing the various elements of systems engineering. QFD is actually a driving force in design, the framework from which various design tools and design elements can be evoked. In fact Schubert sees systems engineering pervading the QFD technique with QFD focusing on the customer requirements primarily while the engineering requirements become secondary. According to Schubert [1989a]:

> QFD is a method of 'mapping' the elements, events, and activities
> that are necessary throughout the development process to achieve
> customer satisfaction. It is a technique oriented approach using
> surveys, reviews, analyses, relationship matrices, and robust design
> all centered on the theme of translating the 'Voice of the Customer'
> into the items that are measurable, actionable, and potentially capable
> of improvement.

History of QFD

Before describing the "how" of QFD, it is useful to examine some of the QFD history. QFD[13] was introduced to Ford in 1984 as a result of findings from a 1983 study mission to

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[12]Referred to as the Fukahara House of Quality approach but also employs the Macabe approach of using a set of four matrices to depict the four phases of design: product planning, parts deployment, process planning, and the production plans stage.

[13]Summarized from Hauser and Clausing, 1988, Schubert, 1989a and Schubert, 1989b.

Japan. The technique really caught the public eye in a 1988 Harvard Business Review (HBR) article by Hauser and Clausing. By the time of the HBR article, two companies, GOAL/QPC[14] and ASI.[15] were actively teaching the technique. Historically, QFD originated at the Mitsubishi Kobe shipyards in 1972. There, Dr. Shigeru Mizuno of the Tokyo Institute of Technology was working and developed "quality tables." These tables eventually evolved into QFD.

However, there is little reference regarding the early QFD work, and this has created some confusion. During the late 1960s and early 1970s, at least four publications, authored or co-authored by Dr. John N. Warfield, were published that directly relate to the QFD concepts. In particular is a 1972 article entitled, "Unified Program Planning."[16] To briefly explain, the Unified Program Planning (UPP) technique uses trees and matrices as a graphical means of displaying the linkages between various program planning steps. To understand the complex, highly interrelated nature of design steps, such visual tools are necessary to accurately and neatly convey the complex information inherent within the systems engineering sequence of steps. Among the major linkages defined are the:

- relationship between planned activities and program objectives,
- interaction between the planned activities and program constraints, and
- measurement system required for relating the progress on the activities to the attainment of the objectives.

Hill and Warfield's [1972] paper limited the discussion to program planning but noted the applicability of the technique to other phases of design. Familiarity with QFD and the UPP technique highlights the similarities and differences among the two techniques. Whether either precedes the other remains a topic of discussion, although recent activities have sought to bring the two techniques together for the sake of CE. Furthermore, why QFD caught on while UPP didn't is unknown. For the purpose of this report, a discussion of the "how" of QFD suffices to depict the technique and structure.

A Description of QFD

QFD starts with a definition of "what" the customer expects from the system. The "whats" are the desired system behaviors or customer attributes. Developing this list is by no means an easy task. Market surveys, group opinion gathering techniques, and group brainstorming processes are used. These techniques need to identify all requirements. Many times unspoken or

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[14]GOAL/QPC stands for the Growth Opportunity Alliance of Lawrence, Center for Quality, Productivity, Competitiveness.

[15]ASI stands for American Supplier Institute

[16]This paper, and other works of Warfield are referenced in Warfield and Kearney, 1989.

expected requirements are missing from the list. The customer will show extreme dissatisfaction if these requirements are not in the end product. Once captured, the relative ranking, or importance, of the requirements is established. This ranking is also a difficult task. A common obstacle is the user's reluctance to prioritize based on an incorrect perception that low-priority needs are ignored. However, these relative rankings are important for trade-off design studies. Figure 8 is an example of the resulting customer requirements list and ranking block.

The next step is to determine the engineering characteristics (the Hows) necessary to meet the customer requirements. Once the list of engineering characteristics is accomplished (Figure 9), the design team determines the interrelationships between the customer requirements and engineering characteristics. Figure 10 depicts how these interrelationships might look. A matrix format provides a much cleaner, easier to understand graphical display (Figure 11) than is depicted in Figure 10. This cleaner look is one of the benefits of QFD.
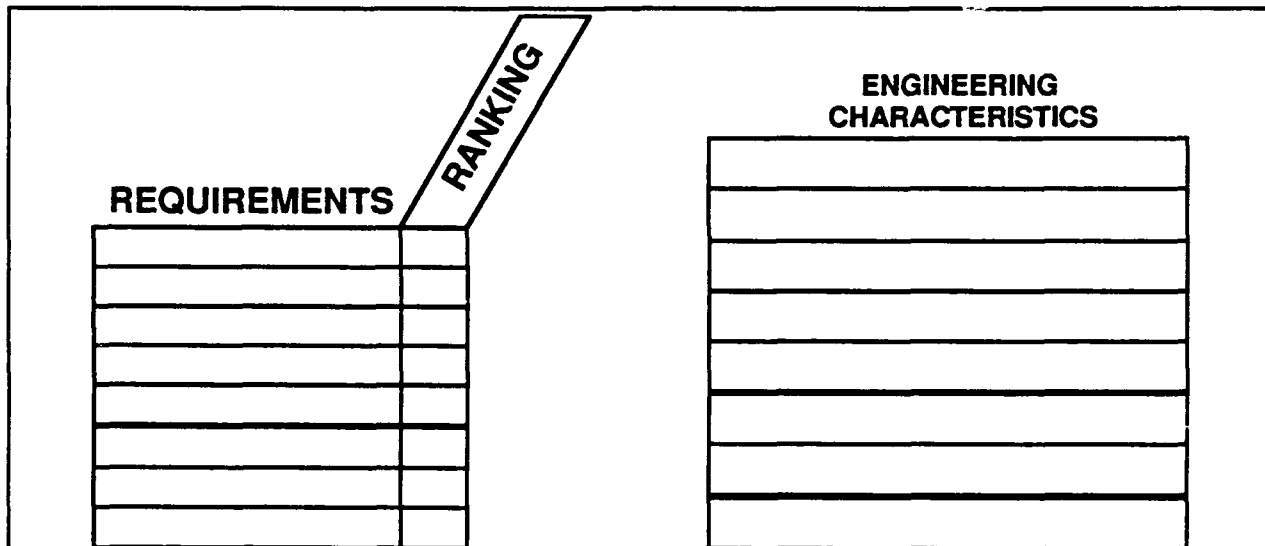

Figure 8. Customer
Requirements (Whats)

Figure 9. Engineering
Characteristics (Hows)

The next step is to determine interrelationships among the engineering characteristics. What relative effect does changing one engineering characteristic have on the other engineering characteristics? These interrelationships are symmetrical in nature and are easily displayed using a matrix roof such as shown in Figure 11 versus using a separate, complete square matrix.
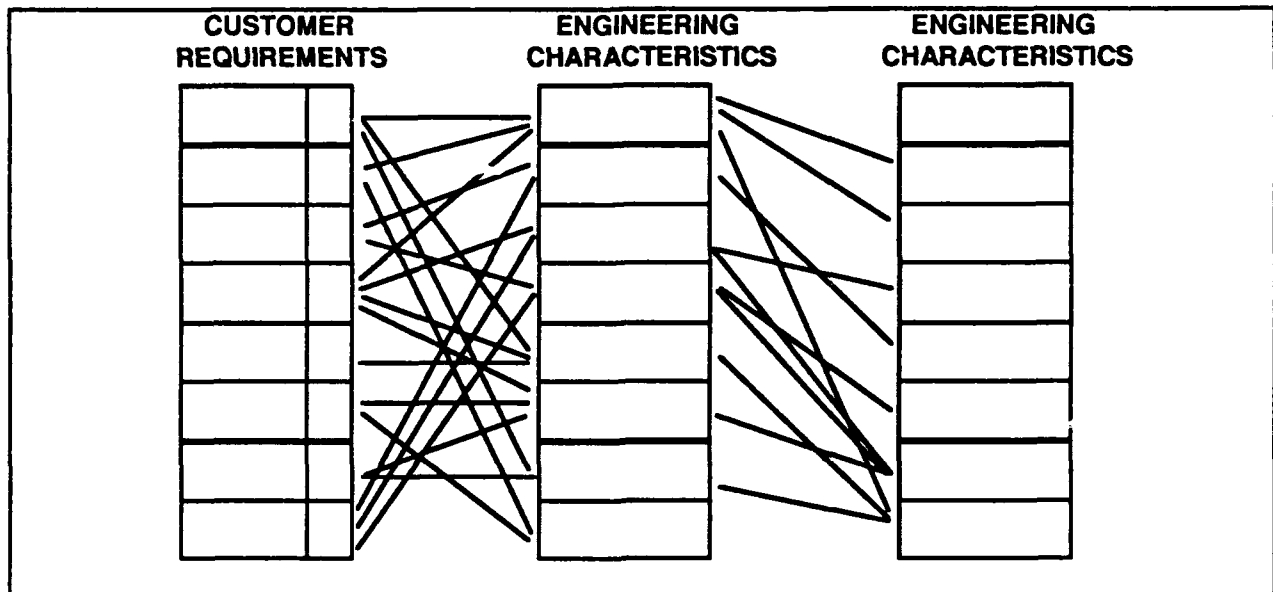
Figure 10. Possible Interrelationships
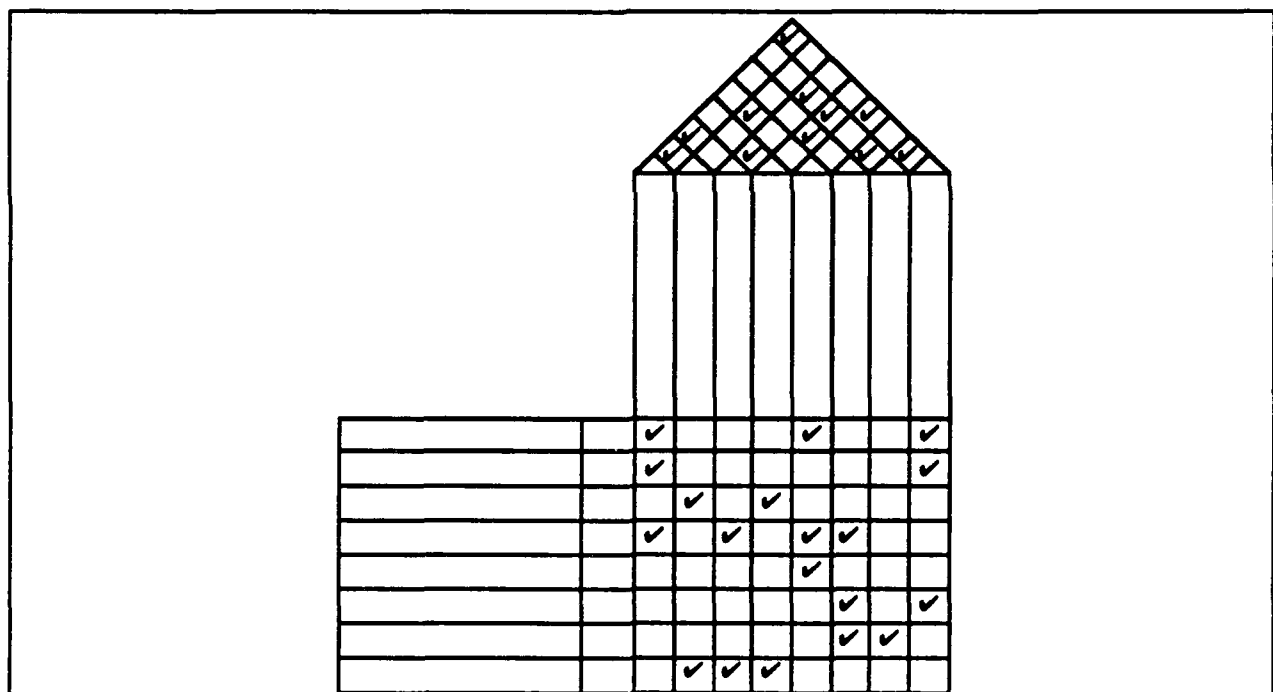
Figure 11. Matrix of Requirements Interrelationships

These design efforts culminate in a complete House of Quality as depicted in Figure 12. Table 1 provides additional information on the labeled areas of Figure 12.

Completing one house doesn't produce the product. At each step of the design decomposition process, the "hows" of each House (the characteristics across the top), become the

"whats" for the next level decomposition. Figure 13 shows this decomposition process, the waterfall relationship. The important points are:

- a multidisciplined cadre of personnel determines the requirements by addressing life cycle issues,
- communication increases among design team members,
- matrices of relationships promote understanding of system requirements, provide relative "sensitivities" among the customer requirements, and document design knowledge,
- all design activities trace back to the original customer requirements,
- better requirements improve program organization and focus, and
- early consideration of life cycle issues means less change later in the design process.
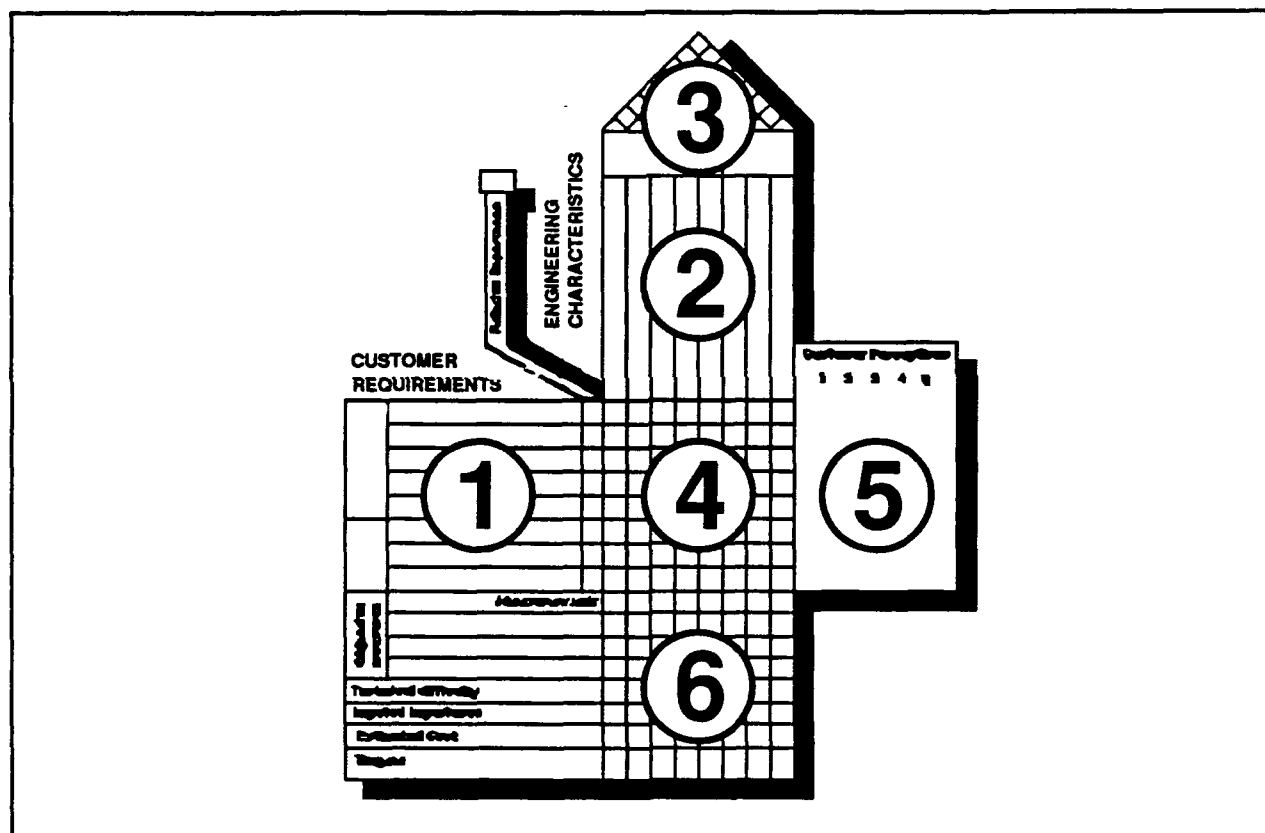

Figure 12. House of Quality [Hauser and Clausing, 1988]

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Table 1. House of Quality Elements

ELEMENT	DESCRIPTION
1	Customer Requirements list and relative prioritization
2	Engineering Characteristic list
3	Engineering Characteristic interrelationship matrix (roof)
4	Customer Requirements - Engineering Characteristics interrelationships
5	Customer Preference Chart used to assess relative competitiveness in a market
6	Technical and Cost Assessment used to allocate resources on elements of a system to provide the most benefit. Uses relative prioritization and engineering difficulty

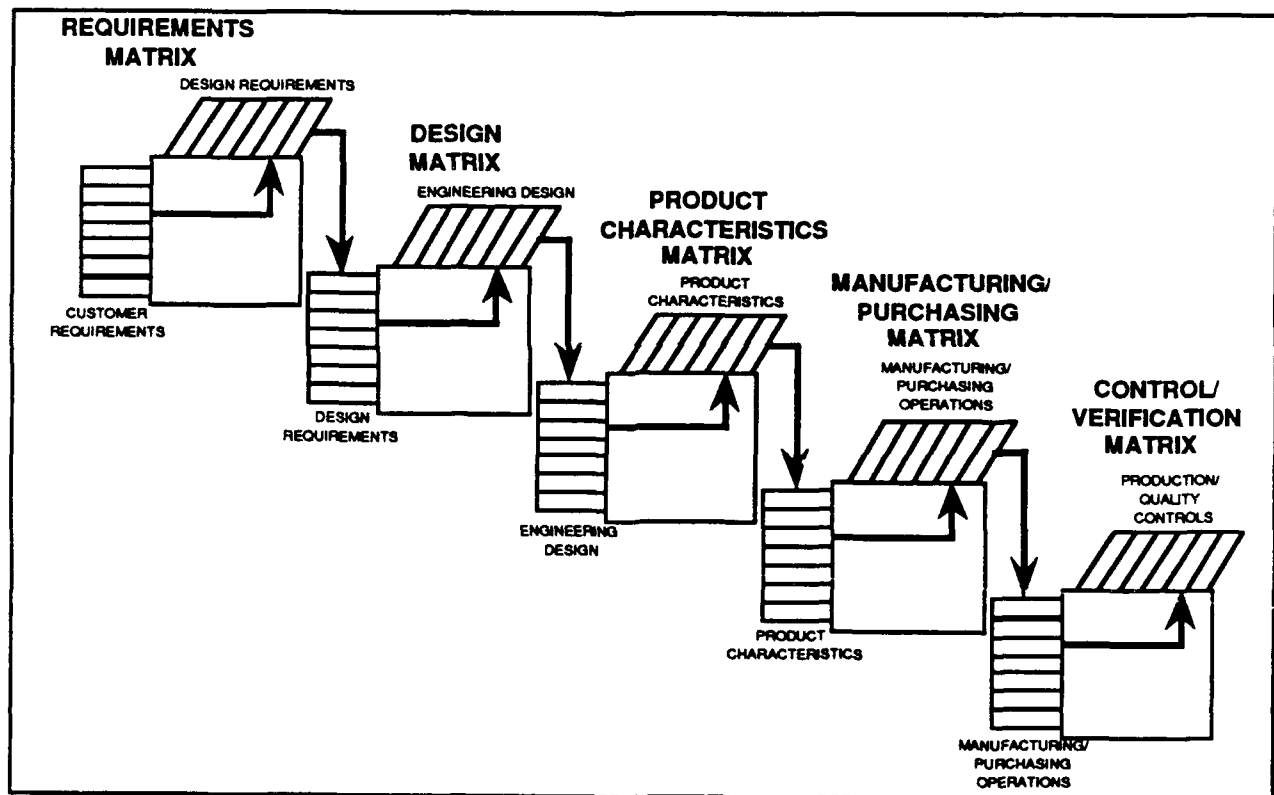

Figure 13. The Waterfall Decomposition Process [ReVelle, 1988]

QFD and Systems Engineering

As previously reported by Schubert, SE pervades QFD. In each technique, requirements are thoroughly defined and design follows a hierarchical decomposition methodology. However, there are some fundamental differences [Schubert, 1989a].

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(1) SE provides inadequate emphasis on understanding the interrelationships among the requirements at the various levels of design. Thus, a great deal of design information is lost in the SE approach while captured in the QFD approach.

(2) SE focuses efforts on the product while QFD emphasizes the design and production process. As a technique for design and organizational quality deployment, QFD accommodates all processes required to produce the product.

(3) SE is generally classified as the "Voice of the Engineer" since it is generally the engineer with responsibility for the requirements. QFD reflects the "Voice of the Customer" since the original customer requirements dictate the design activity.

(4) Finally, SE produces a myriad of documents covering the various system requirements. All too often, there is insufficient correlation among these documents. This fragmentation leads to inadequate definition of some requirements and conflicting requirements between documents [Stanley and Birkler, 1986]. QFD's interrelated matrices depict the design process and provide a means to reconcile conflicting program documentation, a point expanded upon in Section IV.

Clearly, this is not a thorough discussion of QFD nor its relationship to UPP. This discussion has touched upon the main points of the technique. It is hoped that this section has provided a mental image of how such a matrix-based technique might provide a paradigm for a decision support environment accommodating the requirements process environment and containing tools and techniques to enhance that requirements process environment.

VI. CONCLUDING REMARKS

The original purpose of this research effort was to investigate the potential link between QFD and CE. CE encompasses the entire life cycle of the weapon system, from concept development to operational deployment and retirement. QFD is a very methodical approach to design. Broad-based application of the technique to an entire weapon system development effort seems self-defeating. However, selective application of QFD-type tools, techniques, and methodologies are promising and the subject of related research [Pennell and Akin, 1990].

One goal of CE is to bring design considerations to bear early in the design program. For example, it is hoped that consideration of the manufacturing processes concurrently with considerations of the functional design will avoid manufacturing problems and redesign later in the program. Much of the precursor work in DSS dealt with technology designed to support such early design considerations. The selective application of QFD-like techniques quickly led us to examine how QFD could enhance the requirements process within weapon systems acquisition.

Both TQM and CE, as well as the Air Force, recognize how important it is to build and deliver systems the customer wants and will use. QFD tries to capture this "Voice of the Customer."

The problem with examining the requirements process is trying to determine what piece of the process to work on. As previously discussed, there are various levels of management involved in the process. In essence the entire requirements process is driven from the top-down. Policy and general procedures emanate from headquarters level. Once defined, the workers at the MAJCOM and SPO level figure out the exact methods and procedures to accomplish the job. The approach taken in this research was to define the requirements process in a very general, yet complete manner, and this definition represents the perspectives and aspects discussed in Section III. Having thus defined the environment, we presented a set of tools and techniques with capabilities that sufficiently cover the environment as defined by the perspectives and aspects. Such coverage provides a tool set that workers can employ to accomplish the requirements process relatively independent of the way in which the process is currently defined by standards and regulations.

The ultimate objective of all this was to try to define a DSS architecture conducive to use in the requirements process. At a minimum the system must accommodate the current requirements process but, additionally, it must enhance that process. As mentioned, much work was done at AFHRL in the area of decision support systems. One common theme was the desire to influence design, in a positive manner, as early as possible in the weapon system life cycle. The earliest phase is the operational need determination followed by the evolutionary process of weapon system requirements determination, analysis, and management. Our envisioned DSS architecture must accommodate the tools and techniques presented in Section IV for adequate coverage of the requirements process and we see the QFD paradigm offering potential solutions.

Observations

The literature searches and discussions yielded a set of observations about the research opportunity in general.

Observation 1

Both TQM and CE place tremendous emphasis on properly defining who the customer for a product (weapon system) really is and what the customer really wants. Policy on both initiatives is necessarily vague about how to go about accomplishing the feat. It would be inappropriate to dictate how to implement TQM and/or CE considering each must be tailored to the particular organization. The use of technology to assist in the effort is necessary but not sufficient to accomplish the task. Thus any DSS tools and techniques developed and integrated to accomplish

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the functions envisioned by this paper must adopt the philosophy of enhancing, not replacing; human performance and communication among design team members. Such a system will increase the discipline within the requirements process and help meet TQM and CE goals and objectives at all levels of the organization hierarchy.

Observation 2

Recent studies and papers [Ferguson and Hertz, 1990; Kent, 1989; and Miller, 1990] have stressed the need for better top-down planning in the area of operational planning and acquisition to support the operational objectives. We found traceability of requirements was an enabling technique for most of the tools and techniques presented. Furthermore, traceability is an enabling technique to improve top-down strategic and tactical operational planning. The ability to trace requirements from National Security Objectives ultimately to fielded hardware to satisfy operational tasks is a powerful mechanism for:

- budget defense,
- program justification,
- analysis of operational capabilities,
- saving time and resources through effective force deployment and planning.

Observation 3

The use of expert system technology will play a major role in any DSS development effort. Such systems must provide:

- functional knowledge of present system capabilities,
- a representation scheme to depict desired system capabilities in operational settings,
- an ability to identify system shortcomings for a given operational scenario,
- knowledge of past systems and lessons learned,
- an ability to bring such knowledge to bear when necessary,
- consistency and rationality among the requirements as the requirements are defined and refined,
- data presentation, paper and computer-screen, in various formats from single data sources.

Observation 4

As designs become more complex, the computer and computer technology will play an increasingly critical role in the development of the system. In light of the Computer-Aided Acquisition Logistics Support (CALS) initiative and its goal of paperless acquisition environments, systems for defining and managing the acquisition effort must be developed that can interface to and assist the design-decision support environments. Data representation schemes must be capable of storing and manipulating data for design influence, for management oversight, and for analytical tradeoffs and the evolving nature of the design requirements and constraints. Network

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trees and matrices provide effective graphical means to depict complex interactions, such as those found in a weapon system design. DSS technology based on the QFD matrix data presentation paradigm seems well suited to the data presentation task.

Issues to Address

The limited scope of the research task prevented investigation of all the issues and concerns raised. This did not however prevent these issues and concerns from coming to light. Some of these are discussed below.

User Acceptance

Any time DSS technology is developed, consideration must be given to the end-user environment, and in particular the time phasing of system implementation. Failure to consider such things often results in user disregard for the system (i.e., it does not get used). Proposing and developing DSS technology to assist in the definition and management of requirements for weapon systems is a new field. Though bits of technology have been employed to aid the process in the past, for the most part the process is paper based. Introducing computer technology into such an environment will surely meet a cool to lukewarm reception. Thus, the end-user environment must be studied and understood to develop systems that "fit" into the environment and the existing processes. Such a fit is required to help ensure widespread use of the resulting tools, methods, and technologies, particularly as the programs, and their set of requirements, transition into program management during the development and production phases.

Group Support Technology

CE is inherently a team approach to design. This is an observation found throughout the IDA [Winner, et al., 1988] and Pymatuning [1988] studies and supported by a more recent IDA study [Dierolf and Richter, 1990]. The defined process for requirements contained in AFR 57-1 implies a multifunctional team approach to the definition and refinement of weapon system needs and requirements. Further, since the weapon system requirements process involves numerous organizations located around the globe, communication becomes a problem. Functions such as brainstorming and concept selection play a vital role in examining options to meet operational objectives and tasks. The accepted staffing of requirements documents is the "shotgun" approach; send the document out to everyone affected, solicit and centrally incorporate their feedback. An effective DSS for requirements must, at some point, address the distributed nature of the DoD, and business in general. Recent research in areas such as Group Decision Support Systems, Computer

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Supported Cooperative Work, or Global Decision Support Systems will impact future DSS enhancements to the requirements process.

Technological Concerns

Some of the technological concerns were alluded to in the above observations. Other technological issues for future research are:

- data base design to accommodate the complexity of the data and the relationships among the data,
- the role of relational, hierarchical and object-oriented database technology,
- the level of design detail required for an effective system and how these requirements might change over time or through the course of an acquisition effort,
- the impact advanced simulation environments will make on early conceptualizations of operational requirements,
- documentation tagging and management schemes to manage the links between requirements and the documentation containing those requirements,
- data communication technology particularly when dealing with dispersed teams,
- hypertext and Hypermedia technology for navigating through the set of design requirements, and the information associated with each requirement,
- how might the requirements from such a system be represented so that they become constraints when interfaced to a design decision support environment.

QFD Uncertainty

Even though this research proposed QFD as a paradigm for development of a DSS for the requirements process, this proposal must be tempered with realistic insights. First, the QFD methodology is a set of tools and techniques. The methodology involves very detailed information and tremendous discipline. Although this effort focuses on just the requirements process aspect of design, the question comes up concerning QFD for the entire system. Whether QFD can be applied to an entire weapon system is debatable given the tremendous amount of time and effort required for a QFD analysis. Second, there is the question of what portions of the QFD methodology should be applied to the requirements process. In many instances, a DSS based on QFD as we propose is actually employing just the graphical aspects of the methodology. In these instances, the term QFD should not even be used since it causes confusion. Finally, there is a mystique about QFD. It comes from Japan. Nowadays, that automatically brings caution. QFD requires disciplined, multifunctional teamwork not typically associated with America's strengths. It requires heavy upfront involvement, before breadboarding, before mockups. Again this is not a typical aspect of American design, particularly in weapon systems design and development. There are however real benefits from QFD, the methodology, and the graphical devices. Thus, there is uncertainty if a scenario such as depicted in Figure 14 is even possible. What is implied in Figure 14 is that QFD-based tools and techniques assist the mission planners, help translate needs and requirements to weapon system requirements and characteristics. These requirements and

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characteristics become part of the contractual package to industry who must then translate the contractual requirements into design features embedded in the delivered system.
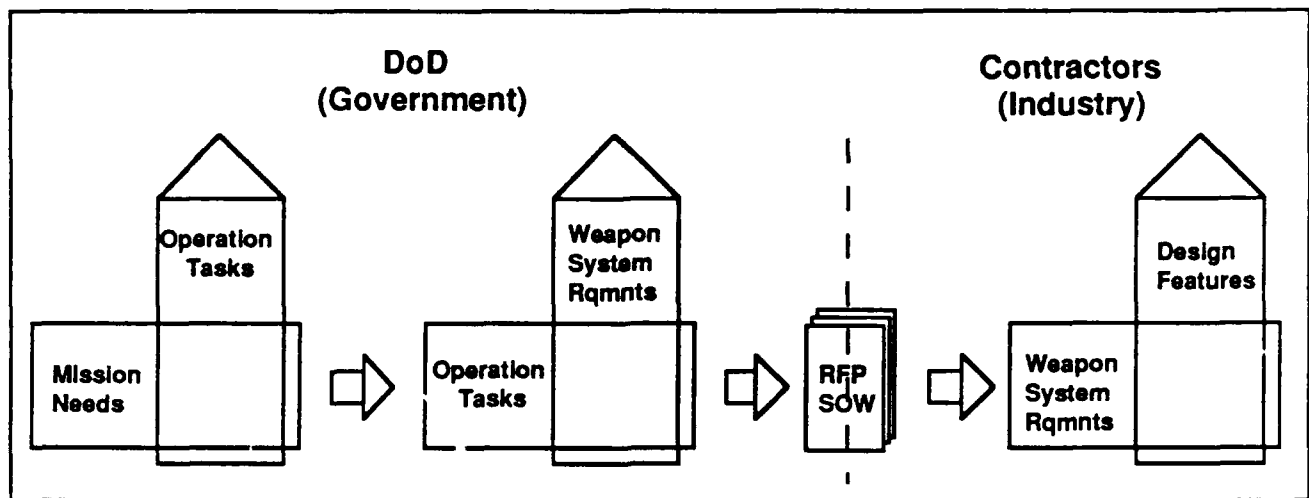

Figure 14. Scenario of QFD in Requirements Process

Conclusions

This research effort arrived at a set of conclusions that serve to guide future research in this DSS for Requirements area.

Conclusion 1

One way to achieve the TQM and CE goals of improved acquisition efforts (i.e., more capability, less cost, less time), is to start the acquisition effort off right. This means improve the requirements process. This improvement must come from the overall requirements process structure, and such issues are being addressed. The improvement must also come from within the infrastructure with tools and techniques to improve and enhance the efforts of the individuals working within the process.

Conclusion 2

The graphical devices, as well as many of the tools and techniques, of QFD can be embedded within a DSS and help provide capabilities to improve and enhance the definition, analysis, and management of weapon systems needs and requirements.

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Conclusion 3

The requirements process is essentially a top-down driven process. The structure of the process is defined in DoD Instructions and in Service Regulations. Within that structure, the needs and requirements ultimately emanate from National Security Objectives and should thus have explicitly defined relationships back to that level. Within the acquisition effort, the system design effort responds to high-level guidance contained in such documents as the SON and the Program Management Directive (PMD). Even though the process is defined and functions in a top-down manner, tools and techniques must be developed from the bottom-up, targeting as users the individuals defining the operational tasks, defining the equipment and capabilities to accomplish the task, and possessing the past experience and knowledge necessary to adequately define the weapon system.

Conclusion 4

Expert system technology can play a key role in capturing past experience and bringing that experience to bear in application-specific cases where a need or requirement must be further refined and traded-off against other system requirements or needs. Expert systems can be employed to ensure consistency among the requirements as well as completeness in the definition process. These systems can promote rapid tradeoffs among competing design requirements and contain algorithms that help "optimize" the design alternative under consideration. Finally, the system automates the more mundane, but necessary, tasks such as documentation generation and maintenance and tailoring of applicable standards.

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APPENDIX A

LIST OF AFHRL DSS DOCUMENTS

Architecture and Integration Requirements for an ULCE Design Environment
DTIC #: AD A194 516
Brei, M. L. et al., Institute for Defense Analyses, IDA P-2063, April 1988

Decision Support Requirements in a ULCE Environment
Vol. I. DTIC #: AD A195 752
ULCE DSS Working Group, Institute for Defense Analyses, IDA P-2064, May 1988

Decision Support Requirements in a ULCE Environment
Vol. II. DTIC #: AD A195 753
Azam, Shapour, et al., Institute for Defense Analyses, IDA P-2064, May 1988

Decision Support Requirements in a ULCE Environment
Vol. III. DTIC #: AD A195 754
Azam, Shapour, et al., Institute for Defense Analyses, IDA P-2064, May 1988

Computer-Aided Group Problem Solving for ULCE
DTIC #: ADA 209 446
Dierolf, David A. and Karen J. Richter, Institute for Defense Analyses, IDA
P-2149,

Product Supportability Issues in the Early Design Phases
DTIC #: AD A218 246
Goldstein, Siegfried, David Owen, Karen J. Richter, Institute for Defense
Analyses, IDA P-2150, October 1989

Aerospace System Unified Life Cycle Engineering (ULCE) Producibility Measurement Issues
DTIC #: AD A210 937
Calkins, Dale E., et al., Institute for Defense Analyses, IDA P-2151, May 1989

Meta-Design -- An Approach to the Development of Design Methodologies
DTIC #: AD E501 228
Rogan, J. E. and William E. Cralley, Institute for Defense Analyses, IDA P-2152,
January 1990

Management of Risk and Uncertainty in Product Development Processes
DTIC #: AD A211 196
Tse, Edison and William E. Cralley, Institute for Defense Analyses, IDA P-2153,
June 1989

Managing Engineering Design Information
DTIC #:
Fulton, R. E., Chou Pin-Yeh, Karen J. Richter, Institute for Defense Analyses,
IDA P-2154, October 1989

A Survey of Research Methods to Study Design
DTIC #: AD A211 213
Brei, M.L., David A. Dierolf, Karen J. Richter, Institute for Defense Analyses,
IDA P-2155, June 1989

Computer Support for Conducting Supportability Trade-offs in a Team Setting
DTIC #: AD E501 219
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Concurrent Engineering Teams
DTIC #: TBD
Dierolf, David A, Karen J. Richter, Institute for Defense Analyses, IDA P-2516, September 1990

Development of the University of Maryland RAMCAD for Electronic Systems
DTIC #:
Richter, Karen J., Institute for Defense Analyses, IDA M-425, October 1988

APPENDIX B

DEFINITION OF ACQUISITION DOCUMENTS
FROM FIGURES 4 AND 6

SDDM	Secretary of Defense Decision Memoranda
PMD	Program Management Directive
DCP	Decision Coordinating Paper
IPS	Integrated Program Summary (now obsolete)
SCP	System Concept Paper
JMSNS	Justification for Major System New Start
SON	Statement of Operational Need
(P)SOC	Preliminary System Operational Concept
Opnl Concept	Operational Concept
Maint Concept	Maintenance Concept/Maintenance Planning
ILSP	Integrated Logistics Support Plan
Mil Stds	Military Standards
SOW	Statement of Work
DT&E	Developmental Test and Evaluation
TEMP	Test and Evaluation Master Plan
OT&E	Operational Test and Evaluation